Kaho'olawe Island Conveyance Commission

Consultant Report No. 3

Unexploded Ordnance on Kaho'olawe: Historical Review, Technology Assessment, and Clearance Planning

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July 1992

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Abstract

The problem of clearing the island of Kaho'olawe, Hawai'i, a former military target range, of surface and subsurface unexploded ordnance (UXO) contamination is examined from historical, technical, and land-use planning points of view. The degree of UXO contamination is estimated, based on historical range use and clearance data. It is found that the expected contamination density is sufficiently low that point recovery (where individual items are detected, located, and removed), rather than area recovery (in which soil excavation and processing is used), will be the more appropriate clearance approach. Technologies currently available, and expected in the future, for the detection and location of buried/subsurface UXO items are assessed to determine their suitability for point recovery operations on Kaho'olawe. It is concluded that presently available techniques, if employed with due concern for proper data collection and processing, will be adequate to the task. A plan is developed for UXO clearance of the island, based on land uses identified in Senate Bill 3088, which established the Kaho'olawe Island Conveyance Commission, and in the *Kaho'olawe Community Plan* prepared for Maui County. The clearance would require a resident team of approximately 120 individuals and would take about five years. The cost, exclusive of infrastructure development, would lie in the range $70M–$75M.

Acknowledgement

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A Note on Hawaiian Orthography

Maopopo iā'oe ka 'ōlelo Hawai'i?
Do you understand the Hawaiian language?

Kaho'olawe is one of the Hawaiian Islands, and many Hawaiian place names (including, of course, "Kaho'olawe" itself) and other Hawaiian words are to be found in this report. Because the report may be read by people unfamiliar with the Hawaiian language, the authors thought it would be useful to include a brief discussion of Hawaiian pronunciation and modern spelling. A more nearly complete discussion of these matters can be found in the *Hawaiian Dictionary* (Revised and Enlarged Edition) by Mary Kawena Pukui and Samuel H. Elbert (University of Hawai'i Press, Honolulu, 1986).

Written Hawaiian, as developed in the mid-nineteenth century by missionaries, was primarily intended for the use of people who already knew the spoken language. As a consequence, the proper pronunciation is not always evident from the spelling. This problem was in large measure solved by the introduction of two additional symbols, one of which (the *macron*) indicated where vowels were to be lengthened, and the other (the *'okina*) indicated where glottal stops were to be inserted between vowels. Spelled using the additional symbols, written Hawaiian can be pronounced nearly correctly by one not familiar with the language, if some basic pronunciation rules are understood.

Vowels

Hawaiian uses the five vowels *a*, *e*, *i*, *o*, and *u*. These have their Latin values ("ah," "ay," "ee," "oh," and "oo" respectively). The vowels, when "long", are given greater stress and duration and are marked with the "macron", viz., *ā*, *ē*, *ī*, *ō*, and *ū*.

Consonants

Hawaiian uses the seven consonants *h*, *k*, *l*, *m*, *n*, *p*, and *w*, as well as the "glottal stop" or *'okina*, marked by the single open quotation mark ('). The 'okina indicates a short stop between vowels like that between the utterances "uh" and "oh" in "uh-oh!"

The remaining consonants are pronounced as in English; but *w* often represents the sound of the letter *v*. The *v* sound is usual after *i* and *e*. Initially or after *a*, either the *w* or *v* sound may occur. After *o* and *u*, the *w* sound is usual. We provide some examples. *Kaho'olawe* is pronounced Ka-ho-'o-la-ve (where the vowels have their Hawaiian or Latin values and with a stop between the two *o*'s). *Hakioawa* is pronounced Ha-ki-o-a-va. *Waikahalulu* is usually pronounced using the *w* sound. The *w* in the word *Hawai'i* will be heard pronounced both ways by different speakers under different circumstances.

Accent

Long vowels are always stressed. In words of four or fewer syllables, the accent usually falls on the next-to-last syllable. Accents in longer words do not follow a general rule. In the word *Kaho'olawe*, for example, accents fall on the second and fourth syllables; but *Hakioawa* is accented on the first and fourth syllables.

Executive Summary

He aha ka puana o ka moe?
What is the answer to the dream?

Perhaps the most important issue associated with the conveyance of the island of Kaho'olawe to the State of Hawai'i is the matter of clearing from the island the ordnance and explosive waste, including unexploded ordnance (UXO), left by nearly fifty years of military bombing, rocketry, and gunnery practice. This issue has been investigated for the Kaho'olawe Island Conveyance Commission by a study team comprising Ballena Systems Corporation of Alameda, California, an engineering and scientific consulting firm, and Donaldson Enterprises, Inc. of Kāne'ohe, Hawai'i, a company specializing in the removal of unexploded ordnance. The purposes of the study were (1) to evaluate the degree of ordnance-related contamination on Kaho'olawe; (2) to conduct an assessment of the technologies presently available, and expected in the future, for the detection and location of buried/subsurface unexploded ordnance on Kaho'olawe; and (3) to develop a plan for the removal of unexploded ordnance from the island. In this Executive Summary we present the results of our study in compact form.

The required degree of UXO clearance from a given area is intimately tied to the projected uses of that area, in that the depth to which the area must be cleared depends on its future use(s). Unfortunately, the only way in which an area can be *totally* cleared involves excavation and soil processing (i.e., sifting excavated soil to remove hazardous items and then replacing the soil and reseeding or replanting the land surface) to a depth approximately equal to twice the greatest expected depth of penetration of the most deeply penetrating bomb or shell which was used in that area. The monetary costs of such an undertaking on Kaho'olawe would be very high. The environmental costs would be monumental. Such a "complete" clearance, however, does not appear necessary on Kaho'olawe: the land uses described in Senate Bill 3088[1] and in the *Kaho'olawe Community Plan*[2] can be accommodated by less drastic means. The clearance plan developed during the study effort is tailored to these projected land uses, most of which, according to current Department of Defense guidelines, will require only surface and shallow-subsurface clearance.

In the remainder of this Executive Summary, we review the projected land uses described in the Senate Bill and in the *Kaho'olawe Community Plan*. We then describe the requirements for clearance of surface and subsurface unexploded ordnance as presently defined by the Department of Defense. Relating projected land uses to these requirements, we develop a set of clearance requirements specifically for Kaho'olawe. We outline the results of our assessments of the degree of ordnance contamination on Kaho'olawe and of the capabilities of detection and location technologies for buried/subsurface UXO. Finally, we review, in summary form, the proposed clearance plan. The "bottom line" of the study effort is summarized as follows:

- Kaho'olawe can be cleared of UXO to the degree required by present land-use plans for the island. The clearance can be accomplished by a resident clearance team of approximately 120 people over a period of about five years. The relatively small size of the team will minimize the environmental burden associated with the clearance effort.

- The cost of the clearance will lie in the range \$70M–\$75M, exclusive of the cost of infrastructure development. Such development should be planned and implemented in accordance with the planned future uses of Kaho'olawe.

- Because of the residual risk of exposure to UXO which can result from imperfect clearance and/or from exposure of previously buried UXO items by the action of wind and water, continuing awareness and safety programs will need to be developed and implemented for Kaho'olawe's permanent residents and visitors.

[1] 101st Congress, Second Session; this Senate Bill established the Kaho'olawe Island Conveyance Commission.

[2] Prepared by EDAW, Inc. for the County of Maui, Hawai'i, June 1982.

Land Uses on Kaho'olawe

Senate Bill 3088 established the Kaho'olawe Island Conveyance Commission and charged it with recommending terms and conditions for returning the island of Kaho'olawe from the United States Government to the State of Hawai'i. Among the specific duties of the Commission were the following:

1. To identify any portions of the land surface of Kaho'olawe that are suitable for restoration to a condition reasonably safe for human habitation, including lands that are suitable for use by the State of Hawai'i for
   (a) parks (including educational and recreational purposes);
   (b) the study and preservation of archaeological sites and remains; and
   (c) the preservation of historic structures, sites, and remains; and
2. To identify any additional portions of such land that are suitable for restoration to a condition less than reasonably safe for human habitation, including lands that are suitable for
   (a) soil conservation and plant reforestation purposes; and
   (b) removal or destruction of non-native plants and animals.

The phrase "restoration of a portion of land to a condition reasonably safe for human habitation" includes, at a minimum, the removal or rendering harmless to activity of all hazardous or explosive ordnance located on or within such portion.

The land uses requiring restoration to a condition reasonably safe for human habitation involve the creation of a park (or parks) and the study and preservation of archaeological and historical sites. We have inferred from these uses that the specific areas which must be made reasonably safe for human habitation would include at least the following:

1. a park headquarters area and its vicinity;
2. roads, trails and camping areas; and

3. the vicinities of the more important archaeological and historical sites[3].

Land uses not requiring restoration to a condition reasonably safe for human habitation are associated with soil conservation, planting and reforestation, and wildlife conservation. While such areas are not necessarily intended for human habitation, they must nevertheless be made reasonably safe for whatever human activities (such as grass and tree planting) are to be conducted thereon.

The *Kaho'olawe Community Plan* of Maui County (1982) also sets forth projected land uses for Kaho'olawe. Land uses described in that plan include:

1. Establishment of permanent base camps (in which permanent structures such as *hālau*[4] may be constructed) in the following areas, as well as in others which may be suitable:
   (a) Honokanaia
   (b) Keanakeiki
   (c) Ahupu Bay
   (d) Hakioawa
2. Establishment of temporary base camps (in which temporary shelters such as tents may be erected) in the following areas, as well as in others which may be suitable:
   (a) Honokoa
   (b) Kūhe'eia
   (c) Kanapou
   (d) Kamohio
   (e) Waikahalulu
   (f) Pu'u Moa'ulanui
3. Restricted uses in the former Target Area:

[3]We have not attempted to identify any specific sites as being of greater interest or importance than any others.

[4]A *hālau* is a Hawaiian long house.

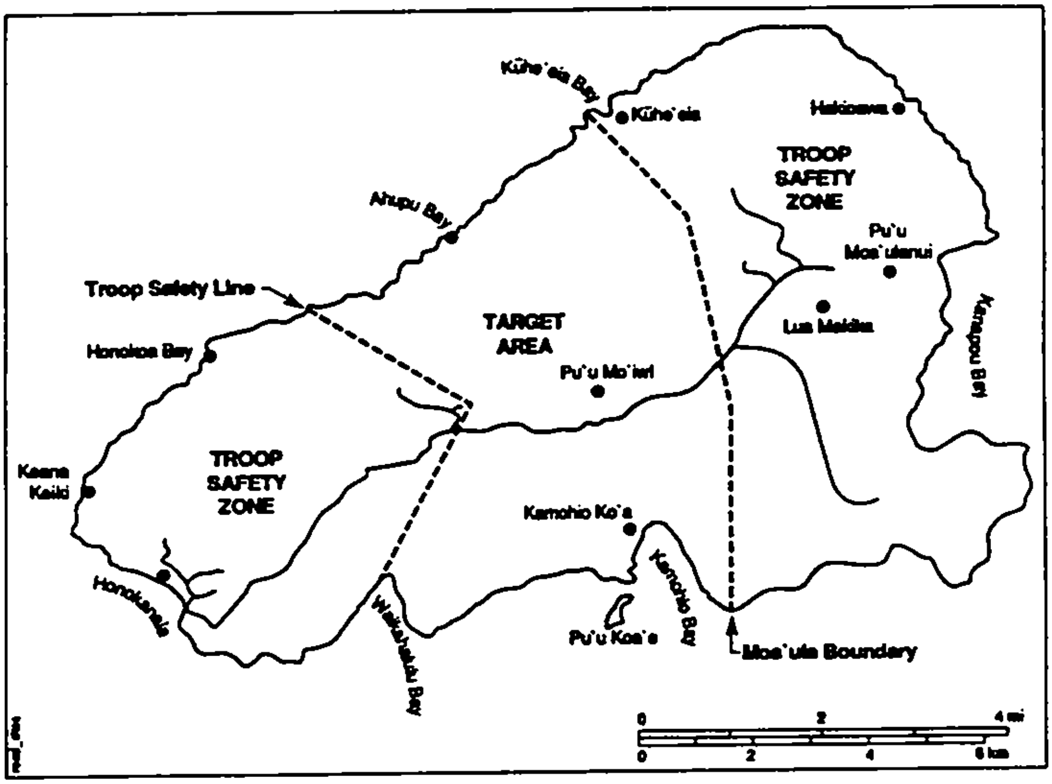

Figure E.1: Map of Kaho'olawe.

(a) ordnance clearance

(b) archaeological studies

These locations are indicated on the map of Kaho'olawe shown in Figure E.1.

We view the land uses suggested in the *Kaho'olawe Community Plan* and those outlined in the Senate bill as fundamentally similar (although, of course, not identical) and mutually consistent. These land uses imply certain UXO clearance requirements, which are discussed in the following section.

Table E.1: Clearance requirements and risks for various land uses (adapted from *Contaminated Area Clearance and Land Use Alternatives*, Department of the Army, Engineers' Study Group, January 1975).

End Use	Clearance Requirement
Maintain current status as impact area or use for disposal area, weapons training site, firing range.	No clearance.
Wilderness park, dump area, cattle grazing (establish restriction on unauthorized excavation).	Surface clearance.
Limited agriculture, tree farming (establish restriction on unauthorized excavation).	Minimum depth clearance to 6 inches.
Farming, golf course, equipment parking (establish restriction on excavation below cleared depth).	Shallow depth clearance to 18 inches.
No land use restrictions provided clearance depth is maximum estimated depth of UXO penetration. If not, establish restriction on excavation below cleared depth.	Medium depth clearance to 15 feet and deep depth clearance to 20 feet.
Land-use as per above alternatives for appropriate depth. Localized clearance applies to building sizes, roads and excavation for utilities, etc. Restrict excavation to cleared area.	Localized area clearance.

UXO Clearance Requirements

There exist guidelines within the Department of Defense for relating projected land uses to UXO clearance requirements. These clearance requirements are expressed in terms of clearance *depths* and are shown in Table E.1. It is important to note that these guidelines are not in any sense *standards*. While the development of clearance standards is under discussion within the Department of Defense, the base of knowledge and experience necessary to develop such standards does not presently exist.

We have concluded from the information shown in the Table and from the land uses proposed for Kaho'olawe that the minimum clearance requirements for the island are as follows:

1. Surface UXO should be cleared from as much of the entire island as possible and *must* be cleared from all areas to which people will have access;
2. Roads, trails, archaeological and historic sites, campsites, and other areas where people will gather should be cleared to a depth of at least 18 inches; and
3. "Deep" clearance will be required only at construction sites for permanent facilities.

We have also assumed that any excavations conducted at locations other than the construction sites for permanent facilities—for example, "digs" at historical or archaeological sites, or tree planting—would be carried out jointly with subsurface ordnance detection, location, and removal efforts at the sites involved, in order to ensure the safety of the individuals participating in the excavations.

Quality assurance or validation of a clearance effort normally involves testing the cleared area against a standard. It was noted above that clearance standards do not yet exist. The procedure now used by the US Government for quality assurance of a sponsored clearance project is as follows:

1. Identify a subset of cleared areas within the clearance project for quality-assurance testing;
2. Employ the best available detection technology[5] to perform 100% inspection of the selected areas; and
3. Accept no failures (that is, passing the quality-assurance test requires that *no* explosive item be found within the test areas).

This procedure should be employed for periodic spot checks during the clearance operation itself and as a part of the post-clearance UXO monitoring program.

UXO Contamination on Kaho'olawe

The study team conducted reviews of all available data relating to ordnance usage and clearance on Kaho'olawe. The purpose of these reviews was (1) to

[5] Which of the several available technologies is "best" will generally depend on the characteristics of the site.

determine the types of ordnance which had been dropped or fired on Kaho'olawe and (2) to estimate the contamination density (that is, the number of potentially dangerous items per acre of land surface). The data were gathered from the available written records, including past ordnance surveys and the surface-clearance records maintained by the Navy; from interviews with military people who had been associated with training or clearance activities on Kaho'olawe; and from a field investigation on the island.

Almost every type of conventional ordnance, ranging from small arms ammunition to 16-inch Naval gun shells and 2000-pound bombs, has been dropped or fired on Kaho'olawe. Most, but certainly not all, of these items detonated as intended.[6] The residual explosive hazards are the consequence of the failure of a fraction of the ordnance to function as intended.[7]

It is very important to estimate the contamination density of unexploded ordnance at a given site before planning its clearance, because the techniques employed for clearance when the density is low (less than 1000 items per acre) are very different from those used when the density is high. If the contamination density is low, the preferred approach is *point recovery*, where UXO items are located and removed individually. In high-density (more than 1000 items per acre) areas, *area recovery* is used: the soil is excavated to the required depth, sifted for ordnance items, and then replaced.

The evidence indicates that the contamination density on Kaho'olawe is far less than 1000 items per acre. The estimated density (including both surface and subsurface ordnance) varies from approximately one item per acre in the region east of the Moa'ula Boundary (see Figure E.1) to three items per acre in the Target Area. The estimated density in the western Troop Safety Zone is approximately two items per acre. Thus mass excavation for ordnance removal does not appear to be called for: point recovery techniques can be used. These techniques depend for their success on the ability of the clearance team to detect and locate buried ordnance items.

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[6]The "dud rate" generally accepted in the military ordnance community is on the order of ten percent.

[7]Particularly dangerous situations arise when the explosive hazards are the result of the presence of mines. These objects are *intended* to detonate when disturbed (in contrast to dud ordnance, which may detonate when disturbed but was not designed to do so). Kaho'olawe has not been seeded with mines.

Detection and Location Technology Assessment

The present state of the art in ordnance clearance technology is reviewed in the document *Range Clearance Technology Assessment* (Naval Explosive Ordnance Disposal Technology Center, Indian Head, Maryland, March 1990). This document is, to the best of our knowledge, the latest available "official" US Government description of the state of the art. The detection and location technologies discussed therein are:

- magnetometry;
- ground-penetrating radar; and
- electromagnetic induction.

We have reviewed this document with some care. We have conducted extensive searches of the scientific and engineering literature, interviewed leading experts in the field of remote sensing, and performed independent technical assessments of these and other technologies. We have also (1) conducted field tests using a magnetometer on Kaho'olawe and (2) obtained soil samples from Kaho'olawe for electromagnetic analysis in order to determine the expected level of performance of ground-penetrating radar in detecting and locating buried unexploded ordnance on the island. The results of our technology assessments are summarized as follows:

- **Magnetometry:** The sensitivity of existing instruments is adequate for the detection of UXO items. The utility of these instruments in magnetically cluttered environments, such as are found on Kaho'olawe and other former ranges and target areas, can be improved through the use of better data collection and processing techniques.
- **Ground-Penetrating Radar:** This technique may be useful over parts of Kaho'olawe's surface for detection of buried items to a depth of one meter or less. One of the problems associated with using ground-penetrating radar in rugged field environments such as Kaho'olawe is the fragility of the instruments themselves.
- **Electromagnetic Induction:** This method of detection is expected to be useful on Kaho'olawe, especially in conjunction with magnetometry.

- **Other Technologies:** Infrared imaging, x-ray and neutron activation of the explosive, and vapor detection techniques have been developed for mine detection. Some of these techniques may be useful in detecting certain types of hazards at shallow depths (six inches or less). They do not appear well suited to the detection of buried ordnance items in general.

We believe that improvements in detection and location technologies will come in the future, given adequate funding support and proper direction of the research. Existing technologies are, however, sufficiently capable to be useful in UXO clearance operations on Kaho'olawe.

UXO Clearance of Kaho'olawe

In this section we present a summary of the UXO clearance plan developed for Kaho'olawe in our study effort. The plan comprises three phases and is based upon the land uses which have been described above. The plan is also founded on the assumption that *risks to personnel involved in clearance operations, and environmental damage to the island resulting from these operations, should be minimized*. Thus the size of the resident clearance team should be relatively small: we estimate the size of this team to be approximately 120 people. Furthermore, area excavation techniques should be employed only where absolutely necessary, i.e., at the sites on which permanent facilities will be constructed. The relatively small size of the clearance team will keep the annual cost low (in the range $13M–$16M per year, exclusive of infrastructure development) and will impose only a modest environmental burden on the island. Limiting the use of area excavation will minimize problems associated with erosion and soil rundown into the surrounding marine areas.

The first phase of the clearance would involve the development of the infrastructure necessary to support the resident clearance team. The base facility would be established at Honokanaia (Smuggler's Cove) and would comprise an enlarged and improved version of the present military facility at that location. Clearance of the vicinity of the base facility (which would be converted in the future, under the land-use scenario described above, to the park headquarters) would be undertaken in parallel with base facility construction. Boat and barge docking facilities would be constructed to ease the problem of supply by sea.

Finally, a network of roads and trails would be cleared and improved to accommodate transport of clearance crews from the base to more remote areas. At the end of this first phase there would exist a cleared base (or park headquarters) facility and its vicinity, a docking facility, and a cleared network of roads and trails.

The second phase would emphasize surface and shallow subsurface clearance of selected areas on the island. We believe that this effort should begin with the former targets themselves, areas where the contamination is heaviest and the vegetation is sparse. This view is based on our perception that these areas present the greatest potential risk.[8] Furthermore, since the vegetation in these areas is sparse, clearance will be relatively easy. If and when the vegetation recovers in these areas, the clearance will become substantially more difficult. Thus time will be of the essence if the decision is made to clear Kaho'olawe of unexploded ordnance: the task will be easier the sooner it is begun.

The second-phase effort would continue with the surface and shallow subsurface clearance of other selected areas on Kaho'olawe, prioritized in accordance with identified land uses. The "permanent" and "temporary" areas which were mentioned in the *Kaho'olawe Community Plan* would be cleared with higher priority during this phase, as would the vicinities of the more important archaeological and historical sites. At the end of the second phase, Kaho'olawe would possess a cleared base/headquarters area, a cleared network of roads and trails, and a set of cleared areas for campsites, archaeological and historical research, nature studies, reforestation, and related activities.

The third phase of the clearance would constitute a continuation of the surface and shallow subsurface clearance undertaken during the second phase, but would be directed toward the clearance of broad areas of lower priority than those identified above for the second-phase effort. At the end of the third phase, essentially all of the land area on Kaho'olawe would be at least surface and shallow-subsurface cleared. Roughly 10% of the island's surface area (the regions designated as "impractical" on the trafficability map of Figure E.2) comprises steeply sloping regions which are difficult of access, either by clearance teams or by visitors to the island. These areas would be the most difficult to clear. Completion of these three phases is expected to take approximately five years.

[8] Every UXO item which is destroyed or removed reduces the potential for exposure, risk, and liability. The highest density of UXO items is found at the former target sites.

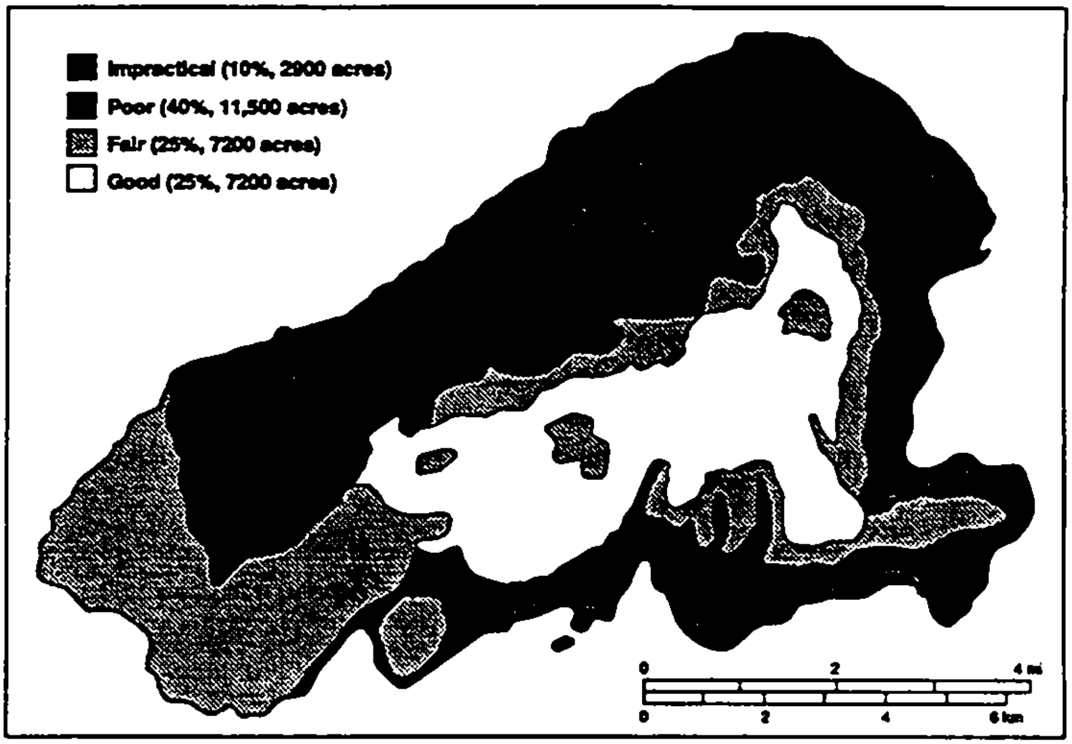

Figure E.2: Trafficability on Kaho'olawe. Areas designated "impractical" are those which will be most difficult to clear.

While it may be possible to remove all the surface and subsurface ordnance from a given area, it is not possible in general to *know* that all the ordnance has been removed. Furthermore, the effects of wind and water erosion can cause previously undetected buried ordnance items to be revealed on the surface. Thus some residual risk of encounter with unexploded ordnance will exist even after clearance efforts have been concluded, and continuing UXO monitoring, awareness, and safety programs will have to be developed and put in place. This continuing monitoring effort can be considered to comprise the "fourth phase" of the clearance project.[9]

Permanent residents on Kaho'olawe (park rangers, for example) will need to be trained as UXO observers and provided with a means for marking found items for later removal by trained explosive ordnance disposal (EOD) personnel. Visitors to the island should be made aware of the possibility of encountering unexploded ordnance and informed of the risks associated with handling UXO items. They should also be made familiar with representative UXO items found on the island.[10] This familiarization might be accomplished with museum exhibits of demilitarized, inert UXO items in the park headquarters and an introductory video presentation which reviews the military history of the island, shows what some of the found UXO items look like *in situ*, and describes the clearance activities conducted or ongoing on Kaho'olawe. Such exhibits would serve as constant safety reminders for rangers and visitors alike.

Concluding Remarks

The problem of surface and buried/subsurface unexploded ordnance on Kaho'olawe, while not trivial, can be dealt with. Indeed, circumstances related both to Kaho'olawe's military history and to its planned future uses are in many ways

[9] Many former World War II target practice areas and ranges were "cleared" immediately following the war, but were not monitored and rechecked thereafter. Therein lies a part of the reason for the accidents which have occurred at some of these sites.

[10] Ideally, visitors to Kaho'olawe would also be escorted by rangers when outside the park headquarters area and would not leave marked roads, trails, or campsites when hiking or exploring the island.

ideal for the rehabilitation of the island, if the decision is made to proceed with clearance of the unexploded ordnance.[11] In particular,

- Kaho'olawe has been used only as a target range; it has not been a war zone. Thus
  - The residual explosive hazard on Kaho'olawe is the result of *failures to detonate as intended* of items fired or dropped on the island.
  - There is no evidence of hazard due to chemical weapons on the island.
  - The island has not been sown with mines, which are *intended* to detonate when disturbed.
- Planned land uses imply a degree of control over visitor access to, and exploration on, the island. This control will contribute greatly to the safety of residents and visitors alike.

We conclude this Executive Summary by noting that UXO contamination, like some diseases, cannot always be completely cured without killing the patient. It can, however, be reduced and managed, and contaminated lands—like Kaho'olawe—can be brought back to an acceptable degree of safety and utility while the restorative forces of nature work to permanently heal their wounds.

[11] The "no-clearance" option, in which access to the island is denied for the foreseeable future, is discussed in the main body of the report.

Chapter 1

Introduction and Overview

Ua awa ka imu, e lāwalu ka i'a.
The oven is ready, let the fish... be cooked.
(Preparations have been made; now let us proceed.)[1]

Kaho'olawe, the smallest of the eight principal Hawaiian Islands, was used as a military training site for aerial bombing, naval gunnery, and related activities from 1941[2] until October 1990, when President Bush directed that the Secretary of Defense cease using the island for such purposes. Shortly thereafter (November 1990), Congress established the Kaho'olawe Island Conveyance Commission, whose purpose was to study and recommend terms and conditions for the return of Kaho'olawe from the federal government to the State of Hawai'i.[3] This Commission will report its findings to Congress in December 1992.

Kaho'olawe has been federal land under the administration of the Secretary of the Navy since 1953, when the island was transferred by Executive Order 10436 (February 20, 1953) from the then Territory of Hawai'i to the Navy Department.[4] Between 1941 and 1953, the island was leased from the Territory to the Army (1941–1945) and then to the Navy (1945–1953).

[1] Chapter heading quotations are taken from Mary Kawena Pukui, *'Ōlelo No'eau* (Bishop Museum Press, Honolulu, 1983).

[2] There exists some evidence that activity of this kind may even have begun as early as the mid-1930s.

[3] Senate Bill 3088, 101st Congress, Second Session.

[4] That status was not changed by the Hawaii Statehood Act of 1959.

Sentiment in favor of terminating military training activities on Kaho'olawe and conveying the island from the federal government to the State of Hawai'i has grown, particularly over the last twenty-five years. The termination of bombing and gunnery practice on Kaho'olawe and the establishment of the Kaho'olawe Island Conveyance Commission are, in large part, consequences of this sentiment and its political expression.

Upon its inception, the Commission determined that studies should be conducted in several areas in order to provide historical and technical data to support the development of its recommendations to Congress. One of those areas was that involving the unexploded ordnance, both on the surface and buried beneath the surface, on Kaho'olawe. The unexploded ordnance (UXO) left on the island after nearly fifty years of target practice and related military training activities presents a substantial impediment to many of its possible future land uses. It is important to determine the extent to which the UXO contamination can be remediated, the cost of such remediation, and the long-term actions necessary for the management of residual UXO hazards and risks.

The specific tasks to be addressed in the course of the ordnance study were intended to support three broad objectives. These are:

1. To develop an "ordnance history" of Kaho'olawe in order to assess the magnitude of the UXO contamination on the island;
2. To conduct a technology assessment of presently available and expected future means for detecting and locating buried UXO; and
3. To develop a plan for clearing Kaho'olawe of UXO to the degree(s) necessary to accommodate possible future land uses.

The study contract was awarded in October 1991 to Ballena Systems Corporation of Alameda, California, an engineering and scientific consulting firm, and its subcontractor, Donaldson Enterprises, Inc. of Kāne'ohe, Hawai'i, a company specializing in the removal of unexploded ordnance. The study team began work in November 1991. This document constitutes the team's Final Report to the Kaho'olawe Island Conveyance Commission.

In the remainder of this chapter we present introductory background information on Kaho'olawe's geography and history. We also provide a general introduction to the issues associated with the clearance of unexploded ordnance from former target ranges and war zones. We then review previous studies which were devoted to the clearance of unexploded ordnance from Kaho'olawe. Finally, we present an overview of the body of the report.

1.1 Background

In this section we present a brief description of Kaho'olawe's land and vegetation and a brief summary of the history of the island. We refer the interested reader to more extensive discussions of these and related subjects. The 1979 *Environmental Impact Statement* [1], for example, is a valuable compendium of information on all aspects of the island and its history; and an extensive collection of documentary information can be found in the *Kaho'olawe Cultural Study* [2]. The geology of the island is discussed by Stearns [3]. An excellent source of geographical information on the Hawaiian Islands is the *Atlas of Hawai'i* [4]. More current documentation on the matters discussed in this section is being prepared under the auspices of the Kaho'olawe Island Conveyance Commission.

1.1.1 Geography: Land and Vegetation

The island of Kaho'olawe, shown on the map of the central Hawaiian Islands in Figure 1.1 and on the island map in Figure 1.2, lies approximately six nautical miles to the southwest of Cape Kinau on Maui. The island is part of the Makawao District of the County of Maui. The partially submerged volcanic crater of Molokini, a popular recreational area for scuba diving and snorkeling, is situated roughly midway between Kaho'olawe and Maui.

Kaho'olawe is a single extinct shield volcano[5] whose age is estimated at 1.5 million years. The island is about eleven miles long and six miles wide, and covers an area of approximately 45 square miles (29,000 acres). Its highest elevation, on the rim of the crater Lua Makika toward the eastern end of the island, is 1480 feet. The northwest and the west sides of the island slope gradually from

[5] A shield volcano is a broad "turtle-backed" mountain built up by quiet eruptions of fluid lava on the sea floor.

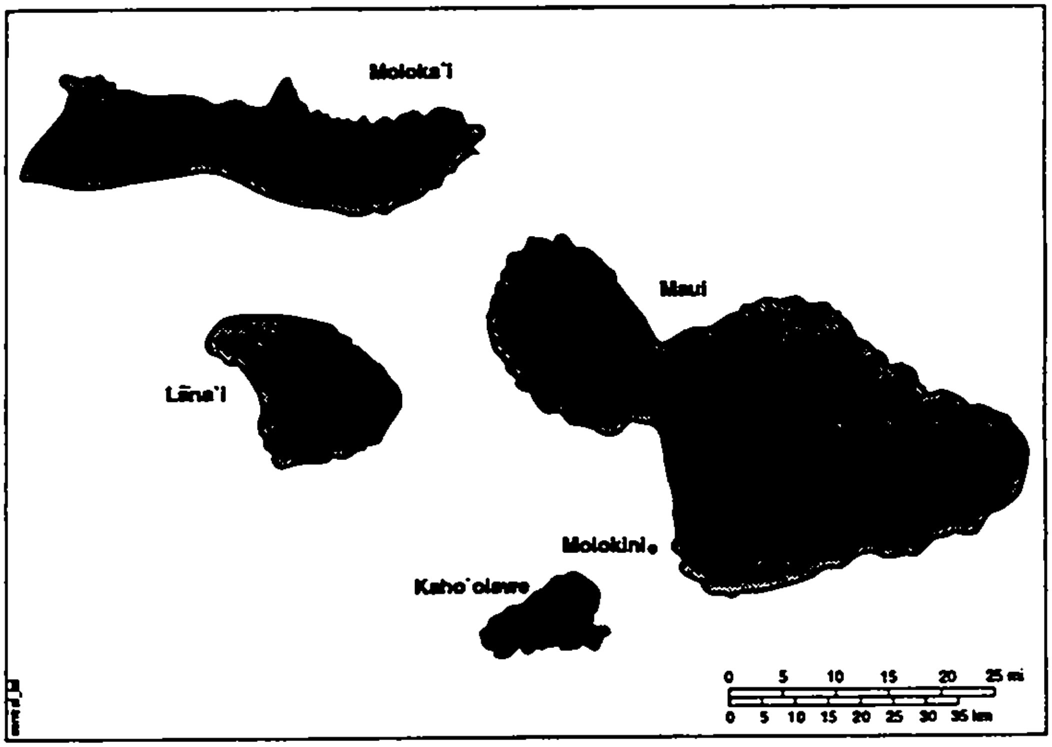

Figure 1.1: The central Hawaiian Islands.

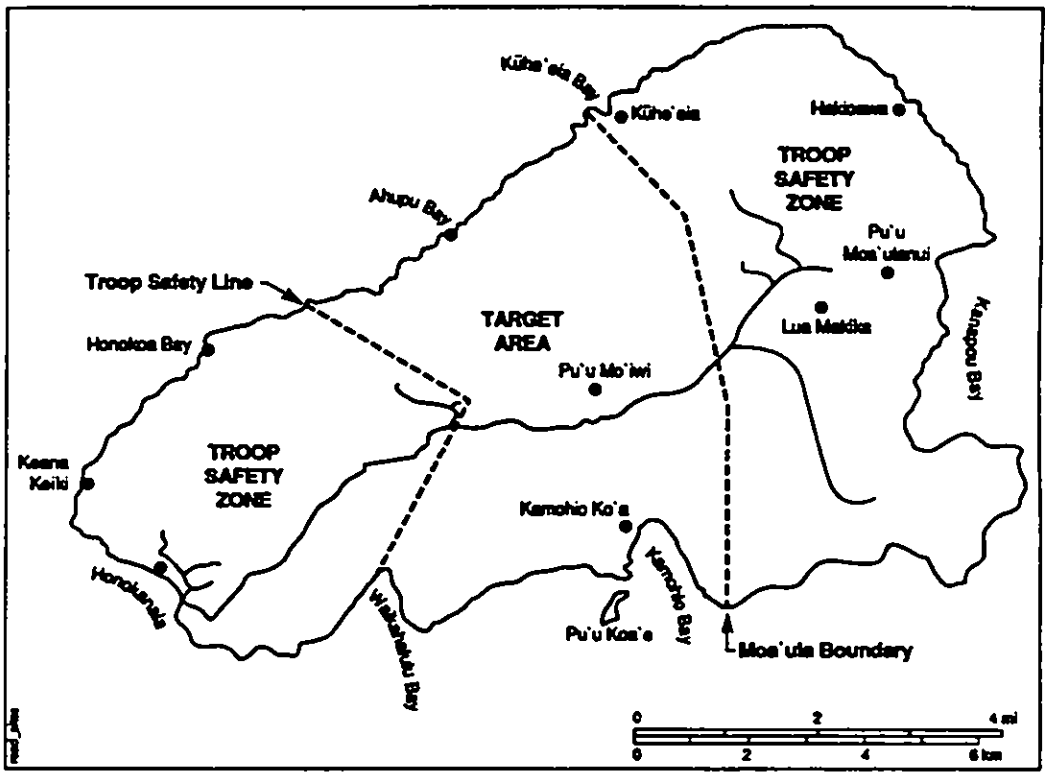

Figure 1.2: Map of Kaho'olawe.

Lua Makika to the coast. To the north, east, and south, this gradual slope is abruptly terminated in a series of sea cliffs up to 800 feet in height.

The prevailing trade winds in Hawai'i come from the northeast. Those bound for Kaho'olawe lose most of their moisture as rainfall on Haleakalā on Maui and are deflected by their passage around that mountain, so that the winds on Kaho'olawe tend to be easterly and dry. In consequence, Kaho'olawe receives relatively little rainfall: only about 20 inches per year, mostly from Kona (southerly) storms in the winter. The vegetation thus resembles that on the leeward sides of the other Hawaiian Islands. Indeed, one of the authors (Baertlein) noted the striking similarities between the vegetation on Kaho'olawe and that found in southern Arizona. Both areas are largely vegetated with grasses and kiawe trees (*prosopis pallida*, which in Arizona are called *mesquite*). The principal types of vegetation on Kaho'olawe are indicated on the map in Figure 1.3. The terrain and vegetation on Kaho'olawe yield the trafficability map shown in Figure 1.4.

It will be noted on the vegetation map that approximately one-third of the island is bare hardpan; this hardpan consists of partially decomposed basalt. The nearly constant wind contributes to the barrenness of the top of the island, by making it difficult for seeds to take hold and by eroding away what little soil remains there. The principal reason for the lack of soil in this region is the absence of vegetation, which is itself due to the past introduction of grazing animals (including goats, introduced in the 1790s; and, later, sheep, cattle, and horses) to the island.[6] The rehabilitation of Kaho'olawe's vegetation has been a continuing concern to the Navy [5] and to other groups concerned with the island's future.

While Kaho'olawe is hardly a tropical paradise—it is windy, arid, and barren in places—it is not unattractive. Indeed, the view from Lua Makika is most spectacular, extending from the peaks of Mauna Loa and Mauna Kea on the Big Island of Hawai'i, visible above the clouds to the southeast, to Moloka'i in the northwest. Furthermore, the island is important for its wealth of artifacts and archaeological sites, and for religious, historical, and cultural reasons best described by the Hawaiian term *aloha 'āina* (love of the land). Kaho'olawe's history is reviewed in the next subsection.

[6] When ranching activities ceased on Kaho'olawe in 1941, a population of goats remained on the island. The progeny of this population were not completely eliminated until 1992.

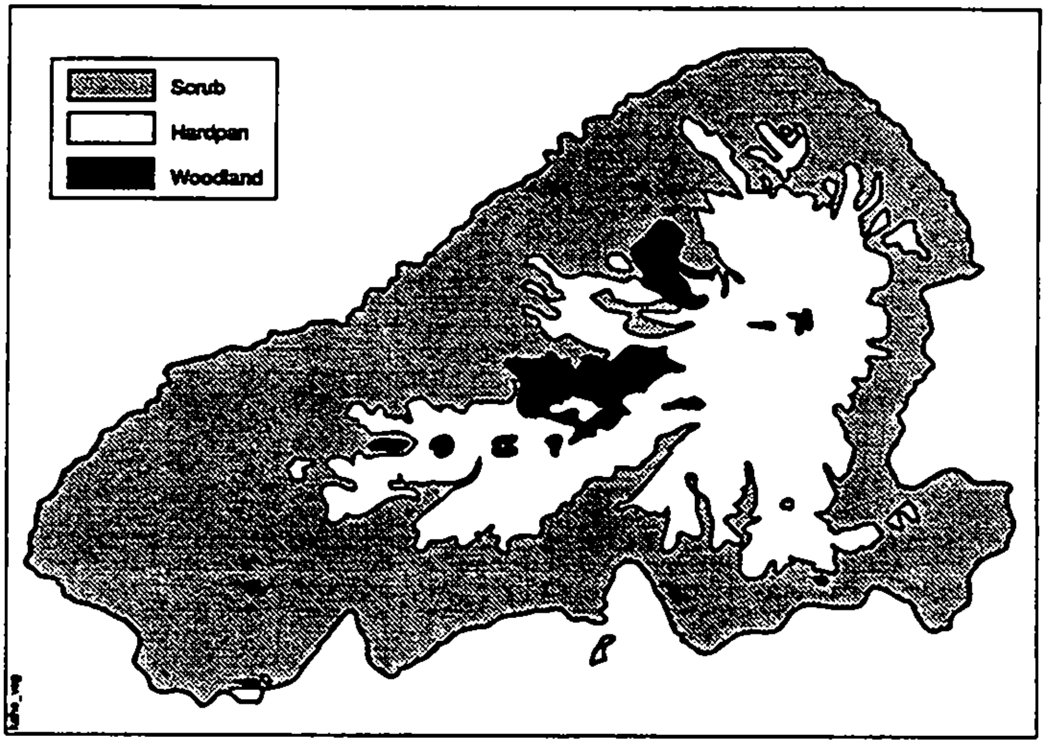

Figure 1.3: Principal vegetation types on Kaho'olawe.

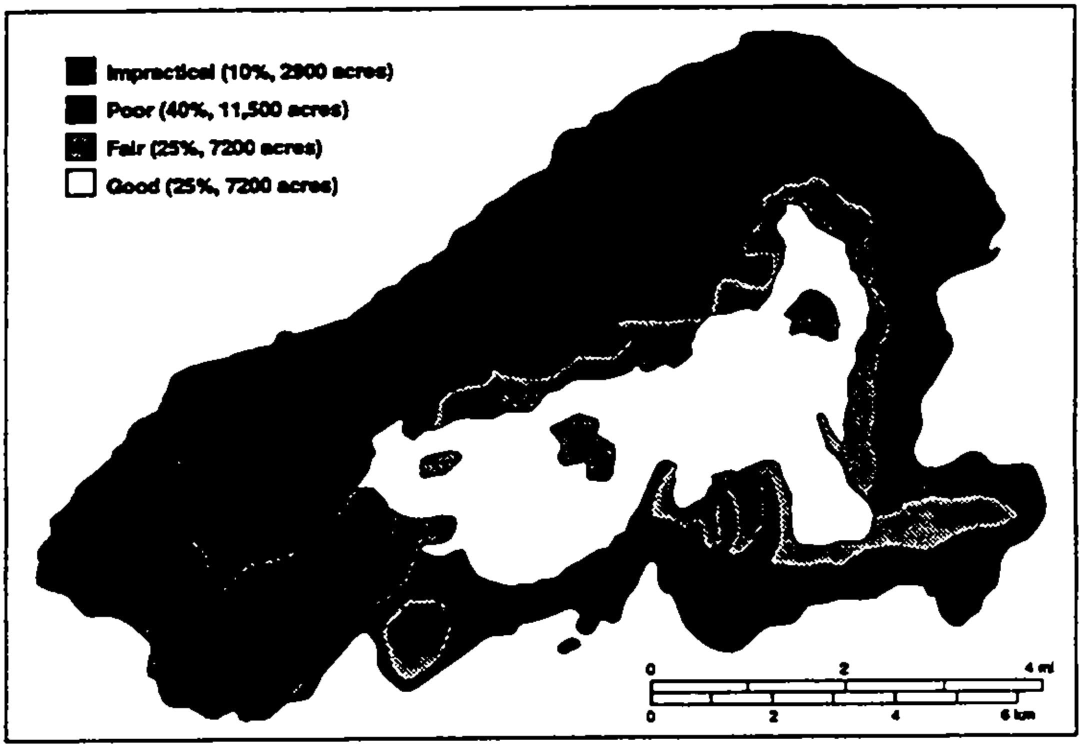

Figure 1.4: Trafficability on Kaho‘olawe. The areas designated as “impractical” comprise steep sea cliffs and gulches difficult of access by vehicles.

1.1.2 Historical Summary

The history of Kaho'olawe can be considered to comprise at least eight distinct periods. These are: *Pre-Western Contact* (pre-1778); *Early Historic* (1778–1825); *Penal Colony* (1826–1853); *Early Ranch* (1853–1910); *Forest Reserve* (1910–1918); *Late Ranch* (1918–1941); *Military* (1941–1978); and *Joint Use* (1978–present). The Military and Joint Use periods are particularly germane to the ordnance study. We present a brief historical summary in what follows. More detailed historical data can be found in [1] and [2].

The pre-contact period is important because it is this period which is represented by the numerous archaeological sites located on Kaho'olawe. There are several hundred such sites on the island, now marked and with access restricted by the Navy. The future scholarly study of these sites is an important issue which is impacted by the presence of unexploded ordnance on the island. Clearance of at least the most important of these sites will be necessary before detailed studies can be undertaken.

Leases of the island from the Hawaiian Kingdom to various individuals and partnerships began in 1859, during the early ranch period. The various lessees intended to raise sheep and/or cattle on the island (except for Benjamin F. Dillingham, who intended for a brief period—1901 to 1903—to grow sugar cane). The last private lessee of Kaho'olawe was Angus MacPhee, who acquired the lease from the Territory of Hawai'i in 1918 and who intended to raise cattle on the island. The lease terms included the requirement that MacPhee eliminate or otherwise remove all the sheep and goats on the island, in order to control soil erosion, which had become severe even fifty years earlier. MacPhee reduced (but did not eliminate) the sheep and goat populations, built water tanks, put up fences and corrals, and planted trees. He spread grass seed and Australian saltbush around the island. Financial difficulties later forced MacPhee into partnership with Harry Baldwin; the partnership, under the name Kaho'olawe Ranch, eventually succeeded.

With the outbreak of war after the Japanese attack on Pearl Harbor, the Army commandeered the ranch sampan and MacPhee subleased a portion of Kaho'olawe to the Army. This lease was extended to the entire island in 1944. The Army transferred the sublease to the Navy in 1945. The Navy held the lease from the Territory until 1953,[7] when Executive Order 10436 (February 20, 1953) effectively removed the island from the control of the Territory of Hawai'i and placed it under the jurisdiction of the Secretary of the Navy.[8] This status did not change when Hawaiian statehood was attained in 1959.

In addition to the bombing and gunnery practice which was conducted on Kaho'olawe from 1941 onward, three high-explosive simulations of the blast effects of a nuclear detonation were performed in 1965. These tests, each of which culminated in the detonation of 500 tons of TNT, were conducted on the southwestern tip of the island. The test series was named Operation Sailor Hat. Its purpose was to test the structural capacity of naval vessels to withstand nuclear blast effects.

Military training activities on Kaho'olawe increased during the Vietnam War. Concurrently, civilian concerns were raised over the nuisance of noise on Maui and the perceived risk of stray bombs and shells landing on the Maui coast. The focal point of these concerns was, initially at least, the Mayor of Maui County, Elmer Cravalho. Mayor Cravalho claimed in 1969 that a stray shell had landed on property which he owned on West Maui; he also claimed, with some justification, that the Navy was not complying with the requirement of the Executive Order to eradicate the population of cloven-hoofed animals on Kaho'olawe.

By 1970 the Navy had limited target practice on Kaho'olawe to the central portion of the island, an area of about 7750 acres now known as the Target Area (the western and eastern portions of the island are called Troop Safety Zones; see the map in Figure 1.2). The Navy also conducted an ordnance-clearing study in 1969 which concluded that approximately 70% of the surface ordnance on Kaho'olawe, and less than 50% of the ordnance in the surrounding waters, could be cleared. The study recommended that the "project be classified as impracticable...."

Mayor Cravalho and an organization called Life of the Land filed suit in 1971 against the continued use of Kaho'olawe as a target area, contending that the Department of Defense and the Navy had failed to prepare an Environmental Impact Statement. The Statement was filed in 1972 and the suit was dismissed.

[7] Angus MacPhee died in 1948 without regaining his lease to Kaho'olawe.

[8] A transcript of Executive Order 10436 is contained in Appendix A of this report.

The Protect Kaho'olawe 'Ohana [family] began protesting military use of the island in 1976, and has remained active in a variety of areas related to Kaho'olawe's future. Stipulations between the Navy and plaintiffs now represented by the Protect Kaho'olawe 'Ohana (PKO) resulted in the entry of a Consent Decree in the case of Aluli *v.* Brown (No. 76-0380, U.S. District Court for the District of Hawai'i). That federal court consent decree affirms the fact that Kaho'olawe's extensive archaeological sites should be protected from harm and provides for progressive cleanup of other areas and general environmental work on Kaho'olawe for preservation and restoration purposes. The PKO has been influential (although not exclusively so) in bringing about the termination of bombing and gunnery practice on the island.

In October 1990, President Bush ordered the Secretary of Defense to cease using Kaho'olawe for target practice and related activities. In November of that year, Senate Bill 3088 (101st Congress, Second Session) was passed, establishing the Kaho'olawe Island Conveyance Commission and charging it with recommending terms and conditions for returning the island to the State of Hawai'i. The activities of the Commission through mid-1991 are summarized in its *Interim Report to the United States Congress* [6]. The Commission will submit its findings in a Final Report to Congress in December 1992.

1.2 Issues in Range Clearance

Explosive shells have been used in warfare since before the American Revolution. Even today, dangerous pieces of ordnance are occasionally found on Civil War battlefields [7]; and in France, ammunition from the Franco-Prussian War (1870) is still discovered, as is ordnance from World War I and World War II [8]. A recent review is given in [9]. All over the world, there exist land areas which, as the result of wars or of related training activities, have been contaminated with unexploded ordnance (some of which is chemical warfare material) and explosive waste. In this section we discuss the problem of unexploded ordnance (UXO) contamination in general terms. We begin with a brief description of the explosive functioning of bombs, artillery shells and related munitions. We briefly review the scope of the worldwide UXO problem. We then describe the organization and structure of the U. S. Government's efforts in clearance of unexploded ordnance. Finally, we discuss some general considerations related to UXO clearance planning.

1.2.1 UXO Contamination: General Considerations

Bombs and gun shells, as well as other ordnance items such as mortar rounds, grenades, and rocket warheads, share many common features. In particular, each has a "main" or "bursting" charge (the principal explosive) which is fired through what is called an *explosive train*, that is, a series of explosions of increasing amounts of decreasingly sensitive materials. The initiation of the train typically occurs through percussion (applied by a form of firing pin) or through heat (applied by an electrical resistance wire). The explosion of the first element in the train (usually the *detonator*) causes the ignition of the second element (the *booster*), which finally ignites the bursting charge. An explosive train is illustrated schematically in Figure 1.5.

Chemical and/or mechanical means are often employed to control the time or place of the detonation. For example, the fuze in an aerial bomb may include a mechanism turned by a small propellor in the bomb's tail. The mechanism "arms" the bomb, typically by freeing a firing pin and allowing it to rest lightly against the detonator itself. When the bomb strikes its target, inertial forces drive the pin into the detonator, initiating the explosive train. The speed of the explosive train may be varied by changing its chemical composition and/or mechanical structure, thus allowing the user to control, for example, the depth to which the bomb penetrates before it bursts.

It is evident from the foregoing that for a bomb or shell to detonate as intended, a number of events must occur in the proper sequence. If an element in the train fails to fire, the bomb or shell does not detonate. The result is a *dud*: an intact, unexploded item of ordnance. Whether the dud is or is not dangerous depends on the reason(s) for its failure to detonate. For example, if the detonator fired but the booster did not, the main bursting charge would be relatively difficult to detonate. On the other hand, if the weapon were equipped with a so-called "cocked-striker" mechanism (similar to a cocked hammer on a pistol or rifle), where a firing pin was held under spring tension away from the detonator and prevented from firing by some temporary obstruction, the bomb or shell could detonate after simply being jarred. Unfortunately, it is not

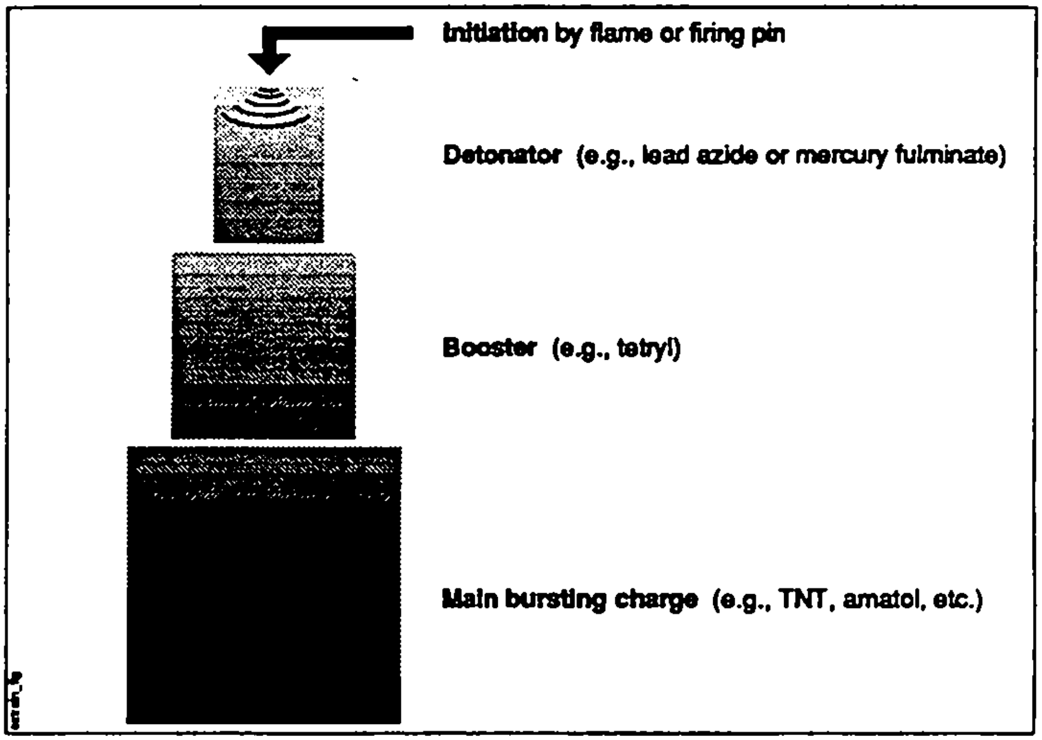

Figure 1.5: Explosive train: schematic.

usually possible to ascertain the reason for dudding from a visual inspection alone. For this reason, duds must be considered armed and ready to detonate when encountered in the field.

When the main explosive charge in a bomb or shell explodes incompletely, a "low-order" (as opposed to high-order, the usual case) detonation is said to occur. In this case, the chemical decomposition of the explosive more nearly resembles burning (deflagration) than detonation. The results of a low-order detonation often include unexploded fragments or chunks of the explosive scattered around the partially disintegrated bomb or shell case.

A small but non-negligible fraction of bombs, shells, and other munitions fails to detonate as intended. This fraction depends on the type of item, the conditions of its use, and other factors. In an inclusive sense, however, the fraction of duds lies typically in the range from five to ten percent. During World War II, for example, between five and ten percent of all US bombs failed to explode; those with delayed-action fuzes accounted for the majority of these duds. During the Vietnam War, the dud rates were as follows for US weapons:

- Artillery shells equipped with the standard point-detonating fuze:[9] 2.5% when set in the super-quick mode; from 5% to 50% when set in the delay mode [10].
- Mortar shells: 10% to 20% during the dry season; 30% or more during the wet season [11].
- Hand grenades: 15% to 25% during the dry season; 40% to 50% during the wet season [11].

The overall dud rate for US weapons in Vietnam is estimated at approximately 10% [11]. It is the duds and the low-order detonations which pose a residual risk to the conversion of former target ranges and war zones to other uses.

The explosive residue of World War II in France makes it necessary for the French to maintain a national team of *demineurs*, specialists in explosive ordnance removal and demolition who travel the country to clear unexploded munitions [8]. This team regularly finds remnants of World War I and the Franco-Prussian War as well as more recently deposited ordnance items. The

[9] That is, a fuze at the nose of the shell whose firing delay is adjustable.

Dutch maintain a team of about 90 people who handle approximately 2000 ordnance disposal cases a year. The Finns, Russians, Poles, British, and other nationalities who were participants in that war (or on whose soil battles were fought) have similar teams [9]. It has been estimated, for example, that Poland's postwar problem with unexploded ordnance may have been the most severe of any country involved in World War II. Over the period from 1945 to 1982, over 88 million items were neutralized on land in Poland [12]. In the Pacific, unexploded ordnance—either duds or stockpiles found in caves or otherwise hidden—is common on the islands which were occupied by the Japanese and from which they were extricated by Allied forces.

The foregoing examples have been directly related to actual conflicts. An additional source of unexploded ordnance contamination is, of course, the use of lands for military training which requires the use of live ordnance. In the United States and its possessions alone, there are (at last count) 1100 Formerly Used Defense Sites (FUDS) thought to be contaminated with unexploded ordnance and explosive ordnance waste [13]. The majority of these are former target ranges. They include the Puerto Rican island of Culebra and the Hawaiian islands of Mānana (Rabbit Island, in Waimanalo Bay, O'ahu) and Kaho'olawe.

Neither the continental United States nor the Hawaiian Islands has been a site of battle for many years, but many areas in the U. S., including Hawai'i, have become contaminated with UXO as a result of military training activities. Although only Kaho'olawe was completely set aside for military use during and after the war, UXO contamination is in fact not uncommon throughout the Hawaiian Islands.[10] The severity of the contamination problem on Kaho'olawe will be explored in the next chapter. We remark at this point, however, that there exist some favorable indications for the clearance and future uses of that island. In particular, *Kaho'olawe has been used only as a target range.* Thus

- The residual explosive hazard is the result of *failures to detonate as intended* of items fired or dropped on the island. The island has not been sown with mines.
- Surface clearance efforts have been ongoing on Kaho'olawe for over a decade.
- There is no evidence of chemical-weapon hazards on the island.

[10]Appendix B contains a review of World War II training areas in Hawai'i.

Unexploded-ordnance contamination is a worldwide problem which has resulted from over a century of war and of training for war. While the problem is, or has been, severe in many places, it is being, and has been, dealt with in at least some of them. The European experience, for example, demonstrates that postwar rebuilding can take place and that life can return to normal, even in areas which were hotly contested over periods of years and where immense quantities of unexploded ordnance have been present. Dealing with the unexploded ordnance contamination problem is not easy. It is expensive, time-consuming, and dangerous; but the risk of death or injury is decreased with every explosive item which is located and detonated or removed. Therein lies the value of the effort.

1.2.2 US Environmental Organization for UXO

Within the United States, explosive ordnance is considered to be a form of environmental contamination regulated under the Comprehensive Environmental Restoration and Compensation Liability Act of 1980 (CERCLA). CERCLA was amended by the Superfund Amendments and Reauthorization Act (SARA) in 1986. Chapter 160 of SARA established the Defense Environmental Restoration Program (DERP). The goals of this program are [7]:

1. The identification, investigation, research and development, and cleanup of contamination from hazardous substances, pollutants, and contaminants;

2. Correction of environmental damage (such as detection and disposal of unexploded ordnance) which creates an imminent and substantial endangerment to the public health or welfare or to the environment; and

3. Demolition and removal of unsafe buildings and structures, including buildings and structures of the Department of Defense at sites formerly used by or under the jurisdiction of the Secretary of Defense.

The Installation Restoration Program (IRP) and the Formerly Used Defense Sites (FUDS) Program constitute the DoD's responses to these goals. CERCLA response action is required at any site currently or formerly used by the

Department of Defense that is contaminated by hazardous or toxic waste, explosive ordnance, or unsafe debris.

The Department of Defense is recognized as the national "expert" in matters related to the safe handling and disposition of military munitions. Section 300.120(C) of the Final National Contingency Plan states that DoD is the removal response authority for incidents involving military weapons and munitions. Within the DoD, the US Army Corps of Engineers' Mandatory Center of Expertise and Design Center for Explosive Ordnance Engineering in Huntsville, Alabama is the focal point for relevant expertise in the Corps of Engineers and the central manager of the explosive ordnance engineering[11] mission for the FUDS program. The technical research arm of the DoD's activities in explosive ordnance engineering is the Naval Explosive Ordnance Disposal Technology Center at the Naval Surface Warfare Center in Indian Head, Maryland.[12]

1.2.3 Clearance Planning

The principal issue to be addressed in clearance planning for a given area is that of striking a balance among possibly conflicting clearance objectives. These include (1) the degree of clearance to be achieved (which will, in general, depend on the planned future use(s) of the cleared area); (2) the level of residual risk remaining after clearance operations have been completed; (3) the degree to which environmental damage caused by clearance operations is tolerable; (4) the cost of the clearance; (5) the duration of the clearance; (6) the technical means available for detection and location of ordnance items; and other factors.

Unexploded ordnance can be found both on the ground surface and buried beneath the surface. The depth to which large bombs and shells can penetrate can reach tens of feet. Clearance operations can thus range conceptually from the relatively simple task of picking up and carrying away—or, if necessary, detonating in place—ordnance items found on the surface, to very difficult, expensive, and complex operations involving deep excavations and soil sifting

[11] Explosive ordnance engineering includes planning, study, design, and remedial action for explosive ordnance contamination in accordance with CERCLA and the National Contingency Plan.

[12] The authors attempted to enlist the assistance of this organization in obtaining data relative to this study and to the general problem of UXO remediation on Kaho'olawe. We were not successful.

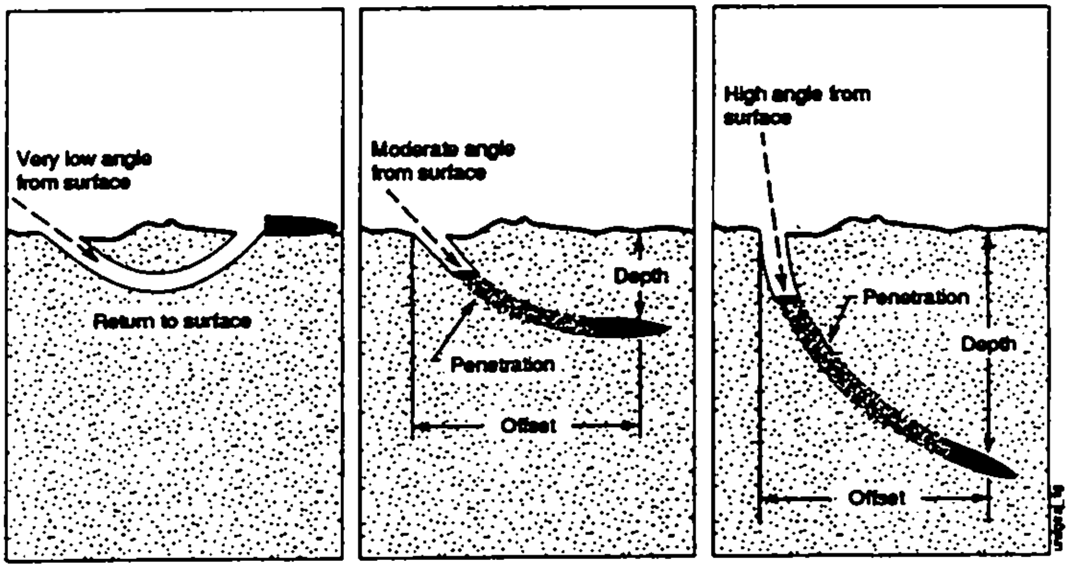

Figure 1.6: Underground trajectories of projectiles.

for the removal of buried UXO items. The depth to which clearance is required depends on the projected future land use.

The underground trajectories of bombs and gun shells are generally J-shaped, as shown in Figure 1.6. At very low impact angles, the munition can penetrate the ground and return to the surface; this behavior is termed "porpoising." At higher angles of impact, the projectile comes to rest below the surface at some distance (the "offset") from its entry point. In addition, the trajectories often swerve to the right or left of the original direction of the projectile. The underground trajectory cannot, in general, be predicted, even with precise knowledge of the controlling parameters: the velocity and direction at impact; the size, weight, and shape of the projectile; and the soil composition.

Different soils provide differing degrees of resistance to projectile penetration. Dry sand has very high resistance; wet clay is relatively easy to penetrate. In general, the greater the water content and plasticity of the soil, the less resistance it offers to penetration. Table 1.1, adapted from [14], shows average and

Table 1.1: Penetration of projectiles into various types of soils.

Projectile Weight (pounds)	Depth of Penetration (feet)							
	Sandstone		Sand and Gravel		Chalk		Clay	
	Average	Probable Maximum	Average	Probable Maximum	Average	Probable Maximum	Average	Probable Maximum
Shells:								
0.25 (20 mm)	0.2	0.5	0.3	0.6	0.3	0.6	0.5	1
2 (37 mm)	0.3	0.6	0.4	0.8	0.5	0.9	0.8	1.5
16 (75 mm)	1	2	1	3	2	4	4	6
30 (105 mm)	2	3	4	6	6	9	10	13
90 (155 mm)	4	9	8	11	10	13	12	17
Bombs:								
100	8	17	9	19	11	19	14	25
500	11	23	13	28	16	29	20	35
1000	14	29	17	33	20	34	24	43
2000	17	34	20	40	24	41	29	52

probable maximum depths of penetration of projectiles of various weights in four types of soils. One will note that the probable maximum depth of penetration of a 2000-pound bomb in clay exceeds 50 feet (15 meters).

A critical parameter to be considered in clearance planning is the estimated density (in number of items per acre, including both items on the surface and items buried below the surface) of the UXO contamination. If this density exceeds a certain threshold (typically 1000 items per acre), the preferred clearance approach is to excavate, sift, and replace the soil over the affected area. This approach is termed *area recovery*. If the density does not exceed the threshold, *point recovery* is preferred: in this approach, items are detected, located, and removed individually. It is evident that remote-sensing capabilities must be available for detection to the required depth if point recovery is to be successful.

1.3 Prior UXO Remediation Studies

Studies of unexploded ordnance (UXO) contamination on, and its removal from, Kaho'olawe began in 1969. The majority of these were conducted directly by the military; the most comprehensive (the Marinco study) was conducted by a private firm under contract to the Navy. In this section we briefly review these earlier studies.

1.3.1 Early Studies (pre-1976)

The earliest studies of UXO on Kaho'olawe comprise several military efforts, many of which were routine surface clearing operations. These efforts are summarized below.

- COMEODGRUPAC (Commander Explosive Ordnance Disposal Group Pacific) report on clearing of ordnance from Kahoolawe Island, 2 May 1969 [15]: this study, conducted in response to COMHAWSEAFRON (Commander Hawaiian Sea Frontier) tasking, discussed the implementation of a proposed clearance plan. Problems in underwater clearance, surface clearance, and subsurface clearance were identified, and personnel and equipment requirements and costs were estimated. The study's recommendation was that the "project be classified as impracticable due to the magnitude of the... operation, the shortage of EOD personnel, and a maximum result of 70% surface clearance only."

- EODMUONE (EOD Mobile Unit One) Ordnance Clearance Operations, 25 August to 3 September 1971 [16]: describes the surface clearance of 177 acres within the Troop Safety Zone. 418 pieces of live ordnance were found and disposed of; 496 inert items were recovered. The live item density was 2.36 per acre.

- EODGRUONE (EOD Group One) Ordnance Clearing Operations, 29 November to 8 December 1971 [17]: describes the clearance of an unspecified area within the Troop Safety Zone; 138 live and 725 inert items were recovered.

- EODMUONE Preliminary Surface Ordnance Survey of Kahoolawe, 2 July to 8 July 1974 [18]: 373 acres were surveyed, with 141 live items found, yielding a live item density of 0.38 per acre.
- COMEODGRUONE (Commander, EODGRUONE) Memorandum concerning EOD Operations at Kahoolawe Island, 13 January 1976 [19]. This is a summary of Navy EOD operations from August 1971 to July 1975. 694 live items were found and disposed of over this period.

The timing of the May 1969 report indicates that it was prompted by protests against the continued use of Kaho'olawe as a target area. The later reports merely document routine surface clearance operations; such operations are a normal component of range maintenance.

In 1975, a team project was performed by a group of individuals at the University of Southern California Systems Management Center. In their report, *Proposed Alternatives for the Clearance of Unexploded Ordnance from the Island of Kahoolawe* [20] (referred to herein as the Kistler report, after the principal author), the authors estimated the cost of clearance to a depth of 15 feet using military bucket-wheel excavation equipment and military personnel at $151M (approximately equivalent to $400M in 1992 dollars, or roughly $14,000 per acre). This approach is similar to one of the options considered in the Marinco study of 1976, discussed below.

1.3.2 The Marinco Study (1976)

During debate on the Military Construction Appropriation Act, 1976, the Department of Defense was directed to study a plan for the utilization of Kaho'olawe and to determine the feasibility and cost of clearing unexploded ordnance from the island and restoring it to a condition which would permit domestic use. In response to this tasking, the Chief of Naval Operations (CNO) requested that the Commander, Naval Sea Systems Command provide CNO with a study of the feasibility and cost of clearing unexploded ordnance from Kaho'olawe. The study was to include all technically feasible clearance options, with no option discounted due to the magnitude or anticipated cost of the effort. This study was conducted by Marinco, Ltd., of Falls Church, Virginia in 1976 under contract to the Naval Sea Systems Command. The primary objective of the Marinco effort was to determine the feasibility and cost of (1) "clearing Kaho'olawe of unexploded ordnance and ordnance-related contamination" and (2) "restoring the island to a condition that would permit domestic use." The results of the study were documented in a final report [21].

The Marinco effort comprised an on-site survey of the surface of Kaho'olawe, conducted over a six-day period and utilizing both Marinco and Navy personnel; reviews of documentation relating to ordnance contamination, physical characteristics, and geological features of the island; and development of clearance options and costs. Six clearance options were considered, ranging from "No clearance; continue using Kaho'olawe as a unrestricted target area" (Option A) to "Clear entire island to depth of 20 feet to allow unrestricted use" (Option B, similar to the approach of the Kistler group). Option A was not considered for obvious reasons; Option B was discounted on the basis of the investigators' judgment that it would have been unacceptable (presumably to the Navy on the basis of cost).

The study concluded that clearance of Kaho'olawe was feasible under two of the six options:

- Option C: "Strip contour entire island to depth of 18 inches; remove major ordnance contamination to additional depth of three feet by use of detection equipment and selective excavation."
- Option D: "Clear 50% of island area using Option C techniques and clear remaining 40% on a selective basis."

It was assumed for all options considered that 10% of the island area was effectively unclearable. The approximate per-acre costs of the "feasible" clearance options, in 1992 dollars, are $12,000 (Option C) and $7,200 (Option D). Note that the area included is 90% of the total area of Kaho'olawe, not all of which would actually be treated; the per-acre cost figures (especially that for Option D) are therefore somewhat low.

The two remaining options discounted in the study were "Clear entire island of surface contamination" (Option E) and "Selectively clear designated areas as determined by land utilization ..." (Option F). Option E was presumably discounted on the basis of its insufficiency for restoring the island to a condition that would permit domestic use. Option F was determined to be outside the scope of the study because it would have required a waiver by the Navy of its requirements governing impact ranges.

No investigation of subsurface UXO contamination was made in the Marinco study. The authors noted that "cost and feasibility analysis is particularly sensitive to subsurface contamination density." They pointed out that making subsurface contamination estimates would require either (1) data of a type which is largely unavailable or (2) the development of a dependable detection and location system.[13] They felt that the only feasible approach to determining subsurface contamination was to clear all debris near the surface to a depth of 12 to 18 inches in order to create a suitable environment for the use of magnetometric or ground-penetrating radar techniques. Neither of these techniques was explored from a technical point of view in the course of the study.

We conclude our discussion of the Marinco study with mention of one of the assumptions which guided that effort: "There will be no constraints on the operation of heavy equipment or detonation of live ordnance on land due to environmental or ecological considerations." On the basis of this assumption, broad-area excavations were the central feature of the two acceptable options (C and D). The authors of the present report believe that (1) broad-area excavations will not be necessary to accommodate the land uses described in Senate Bill 3088 and in the *Kaho'olawe Community Plan* [22] and (2) such excavations would not be tolerable in any event for environmental reasons.[14] As will be seen, the approach proposed herein for the remediation of Kaho'olawe is to let the clearance effort be dictated by proposed land uses: this approach is effectively that of the (discounted) Marinco Option F, which was at that time considered to be out of scope.

[13] It is interesting to note that an experiment was conducted, as part of the Marinco study, to determine the penetration depth of bombs. Eight dummy bombs were dropped under controlled conditions. Only three of the eight were found.

[14] We do, however, assume that detonation of live ordnance in place, if necessary, will be acceptable. Indeed, much of the ongoing tree-planting effort uses explosives for making the holes in which the trees are planted; and live ordnance is routinely detonated in place in the Navy's present surface-clearance program.

1.3.3 Post-1976 Studies

We are aware of one post-1976 study related to the clearance of buried UXO items from Kaho'olawe. The Naval Explosive Ordnance Disposal Technology Center contracted with the Department of the Interior, Geological Survey, in 1980 to test various geophysical instruments on Kaho'olawe for the purposes of detecting buried ordnance. The field tests were performed but the laboratory soil testing and analysis, and the interpretation and report writing, were never completed because funds were not appropriated to complete the project [23].

Surface clearance of Kaho'olawe has been conducted by the Navy on a monthly basis for over a decade. We will make use of the clearance data collected as part of this ongoing effort in developing contamination estimates for the island (Chapter 2). In July 1989, normal monthly sweep operations were suspended because of the need to use EOD personnel in support of road construction. Magnetic and induction locators were used in attempts to find buried ordnance items at the construction site, with mixed results because of the large numbers of false alarms caused by the presence of shrapnel and by the magnetic character of the soil. We consider this matter in Chapter 3.

1.4 Overview of the Report

The occurrence of wars throughout the world and the training activities associated with preparing for them, especially over the last century, have produced immense quantities of unexploded ordnance contamination over thousands of square miles of the earth's surface. The degree of UXO contamination on Kaho'olawe is explored in the following chapter, where we present the results of our ordnance-history study and describe our assessment of the situation on that island. We also discuss the implications of the estimated degree of contamination on Kaho'olawe for the clearance of unexploded ordnance from the island. The technical means presently available, and those expected to become available in the relatively near future, for detecting and locating buried UXO are described in some detail in Chapter 3. Their suitability for application on Kaho'olawe is assessed in the context of the particular geographic conditions prevailing there. Then in Chapter 4 we present a plan for the clearance of UXO from the island in the context of proposed land uses, beginning with a general review of clearance requirements in relation to possible land uses. Chapter 5 concludes the report with a summary of results and recommendations for further work. These recommendations are related both to the general problem of detecting, locating, and removing subsurface UXO from former military areas and to the particular problem of environmental remediation on Kaho'olawe. The Appendices contain supporting information on certain topics addressed in the main body of the report.

Chapter 2

UXO Contamination on Kahoʻolawe

Pā ka makani o ka Moaʻe, hele ka lepo o Kahoʻolawe i Māʻalaea.
When the Moaʻe wind blows, the dust of Kahoʻolawe goes toward Māʻalaea.

In this chapter we develop an assessment of the present state of UXO contamination on Kahoʻolawe by reviewing the "ordnance history" of the island. We draw inferences from the estimated degrees of contamination on different parts of the island in order to determine the preferred approaches to their clearance. It will be shown that the density of unexploded ordnance items is such that *point recovery*, rather than *area recovery*, techniques are to be preferred.

Much has been written concerning the bombing and shelling of Kahoʻolawe during and after World War II. Some excerpts from popular accounts written soon after the end of the war follow:

> "In May [1944] they [the 4th Marine Division] joined the 2nd Marines at Malaaea [sic] Bay in a detailed Marianas campaign rehearsal which involved a mock invasion of the island of Kahoolawe, with live ammunition used for naval gunfire and aircraft support [24, p. 189]."
>
> "The 4th and 5th [Marine divisions] trained at their separate camps [in late 1944] and then joined for ship-to-shore rehearsals at Malaaea and Kahoolawe before shoving off for Iwo Jima [24, p. 190]."

> "The deserted island of Kahoolawe became known as Little Tarawa because of the number of naval shellings and practice assaults which it underwent, while Malaaea Bay itself was being constantly churned by waves of landing craft [25, p. 9]."
>
> "Kahoolawe is by all odds the most artillery-battered island in the Pacific. It has been stated that more gunfire was poured into this place than either Iwo Jima or Okinawa. For it was here, on what was called "Little Tarawa", that the full-dress naval rehearsals of invasion were staged, as many as 800 vessels from battleships to destroyer escorts, taking part from time to time in the bombardment of its beaches and hills. The middle of the island afforded a fairly safe spot for gunfire observation [25, p. 249]."

In the remainder of this chapter we describe the past and present targets on Kaho'olawe in order to identify the areas where heavy ordnance contamination is most likely to be found. We then review ordnance survey and clearance data in order to estimate the degree of ordnance contamination at various locations on the island. Finally, we draw conclusions regarding the clearance approach which is expected to be most appropriate for Kaho'olawe.

2.1 The "Military Geography" of Kaho'olawe

Kaho'olawe is divided into three regions. These include, first, the Troop Safety Zone, the area to the west of a Troop Safety Line which runs from the head of Waikahalulu Bay to UTM (Universal Transverse Mercator) grid point 470734, near the Air Operations Spotting Tower, and thence to a point (437756) just to the west of Maka'alae; second, the Target Area, between the Troop Safety Line just described and another (also known as the Moa'ula Boundary) which runs from Kuakaiwa to grid point 517733, thence to point 510768, and finally to point 489791, near Kūhe'eia Bay; and finally, the eastern portion of the island. Target practice was restricted to the Target Area after 1970; but the entire island has been used at one time or another for target practice.

Sixteen air-to-surface (Alfa), five ground, and 15 surface-to-surface (Sierra) targets are located in the Target Area. Older targets, which have not been used in recent years, were also located in the Troop Safety Zone (the old West

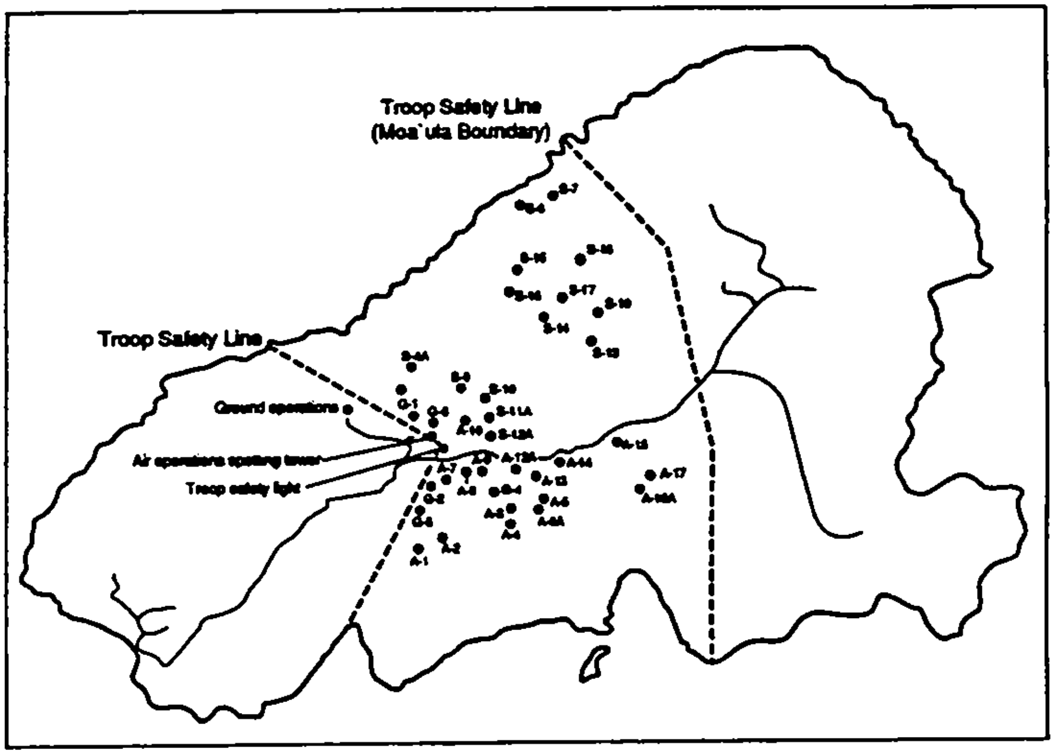

Figure 2.1: Locations of present targets on Kaho'olawe.

Airfield,[1] and air and shore bombardment targets) and in the region east of the Moa'ula Boundary (the old East Airfield and two Sierra targets). The current target locations are indicated on the map in Figure 2.1. While ordnance contamination is expected to be heaviest in the near vicinities of these targets, the entire island was used as a free-drop area on targets of opportunity during World War II and the Korean War. Thus, although the degree of contamination will vary over the island, there appears to be no area which was never used as a target in some sense. Descriptions and precise locations of the present targets are given in Table 2.1.

Reviewing the available documentation concerning the types of ordnance which have been dropped, fired, or otherwise expended on Kaho'olawe, one

[1] There is also a "West Airfield" target in the Target Area; see Table 2.1.

Table 2.1: Descriptions and locations of present targets on Kaho'olawe.

No.	Description	UTM Coordinates
A-1	Rock ring – 25 feet	466717
A-2	Rock ring – 25 feet	470719
A-3	Rock ring – 25 feet	481723
A-4	Rock ring – 100, 500 and 1000 feet (loft bombing target)	481720
A-5	West airfield	488725
A-6A	One truck	487723
A-7	Complex target – 10 foot bull, 100 and 200 foot rings (inert only)	469730
A-8	No. 1 strafing target	473730
A-9	No. 2 strafing target	475730
A-10	MK-76 / 2.75 FFAR target – 10 foot bull, 100, 200 and 300 foot rings	476739
A-12A	One truck	482729
A-13	(Z-convoy) West convoy	486728
A-14	Central convoy	490731
A-15	East convoy	501733
A-16A	Tire ring	505726
A-17	SAM site	506728
G-1	Three trucks	465739
G-2	Three trucks	467729
G-4	Three trucks	476727
G-5	Three trucks, barrels	465725
G-6	One truck	468738
S-4A	One truck	465747
S-6	Rock pyramid target – 6 x 6 by 6 feet high	483774
S-7	Rock pyramid target – 6 x 6 by 6 feet high	490776
S-8	Jeep target	464743
S-9	Drop tank (night illumination target)	474742
S-10	Truck target (night illumination target)	477741
S-11A	North end truck convoy	478739
S-12A	South end truck covoy	478736
S-13	Rock ring target – 25 feet (reverse slope ring target)	489754
S-14	Rock ring target – 25 feet (reverse slope ring target)	484758
S-15	Rock ring target – 10 and 25 feet	484763
S-16	Truck target	483760
S-17	Truck target	491759
S-18	Rock pyramid – 12 x 12 by 8 feet high	494765
S-19	500 yard x 600 yard target	498756

finds that almost every type of conventional ordnance in the U. S. arsenal from World War II onward is represented. The largest items are 2000-pound bombs and 16-inch naval gun shells; the smallest are rifle and pistol ammunition.

2.2 Ordnance Contamination Estimates

In gathering information regarding the degree of unexploded ordnance contamination of Kaho'olawe, the study team examined the documentary record, conducted interviews with active-duty and retired military personnel associated with ordnance-related activities on Kaho'olawe, and performed a field inspection on the island. Documentation describing another surface and subsurface clearance effort in an area similar in important respects to Kaho'olawe was used to draw conclusions regarding the correlation between observed surface contamination densities and inferred subsurface densities there. The contamination estimates resulting from these efforts are developed in this section.

The only way in which one can exactly determine the degree of unexploded ordnance contamination at a given site is effectively to clear it: that is, to find, identify, and remove every item. In practice, one estimates the contamination level by investigating a set of sample locations and drawing inferential conclusions for the remainder of the area. This was the procedure followed in the Marinco study and in the present study to develop the surface contamination estimates which are discussed in the following.

2.2.1 Surface Ordnance Surveys

The most useful documents covering the period up to 1979 were the 1976 Marinco study report [21] and the 1979 Environmental Impact Statement [1]. Navy range-clearance reports for the period 1983–1990 provided more recent data on surface ordnance contamination densities.

2.2.1.1 Marinco Surface Survey Data

The Marinco survey of 1976 [21] covered an area of 1,656 acres (5.8% of the total area of the island), of which 544 were in the Troop Safety Zone and 1112 were in the Target Area. In addition, a broad area reconnaissance was conducted along a 35 kilometer (22 mile) path, most of which lay in the region east of the Moa'ula Boundary. The results of that survey are summarized below:

- The density of hazardous items in the Troop Safety Zone was estimated at 0.27 items/acre (that is, approximately one item for every 3.7 acres).
- The density of hazardous items in the Target Area ranged from 0.03 to 0.91 items per acre at the specific sites surveyed, with an average density of 0.37 items per acre (that is, one item every 2.7 acres).
- The density of hazardous items in the region east of the Moa'ula Boundary was thought "highly unlikely... [to] approach even... 0.03 items/acre."

The results of the Marinco survey are in close agreement with those obtained in a 1974 survey conducted by the Navy [18], in which the most probable density for the combined Troop Safety Zone and the Target Area was estimated to be 0.38 items/acre.

2.2.1.2 Navy EOD Surface Survey Data

The study team has collected and examined surface ordnance data gathered monthly by EOD Mobile Unit One as part of the Navy's ongoing surface-clearance effort. The data cover the period from January 1983 through December 1990. These data have been analyzed and are described in the following.

From January 1983 through November 1986 the range-clearance data do not include descriptions of the items found; from December 1986 on, the ordnance items removed or destroyed are identified by type. We have concentrated our study on the reports from this later period. Table 2.2 contains a summary of the reports, indicating the area swept, the total number of ordnance items removed or destroyed, and the weight of scrap and inert ordnance recovered for each quarter during the four-year period. The total area surveyed during the period is 7726 acres, nearly 27% of the area of Kaho'olawe. The table also indicates the number of items of 20 mm and smaller cartridges and projectiles

Table 2.2: Summary of range-clearance data: December 1986 to December 1990.

Time Period		Area (acres)	Ordnance Items Found	Items 20 mm or Smaller	Scrap Weight (lbs)
December	1986	97	10	0	150
1st Quarter	1987	995	313	100	15,090
2nd Quarter	1987	334	862	765	98,664
3rd Quarter	1987	508	2026	1767	56,550
4th Quarter	1987	536	1587	1248	62,945
1st Quarter	1988	651	2762	2607	57,803
2nd Quarter	1988	691	5035	4653	86,423
3rd Quarter	1988	652	2621	2421	64,147
4th Quarter	1988	317	1982	1830	20,699
1st Quarter	1989	370	1759	1703	20,454
2nd Quarter	1989	605	3617	3573	23,208
3rd Quarter	1989	289	1785	1771	9,893
4th Quarter	1989	313	2011	1999	6,482
1st Quarter	1990	199	2750	2748	17,005
2nd Quarter	1990	426	2768	2750	28,922
3rd Quarter	1990	176	2960	2952	27,115
4th Quarter	1990	67	3244	3235	20,016

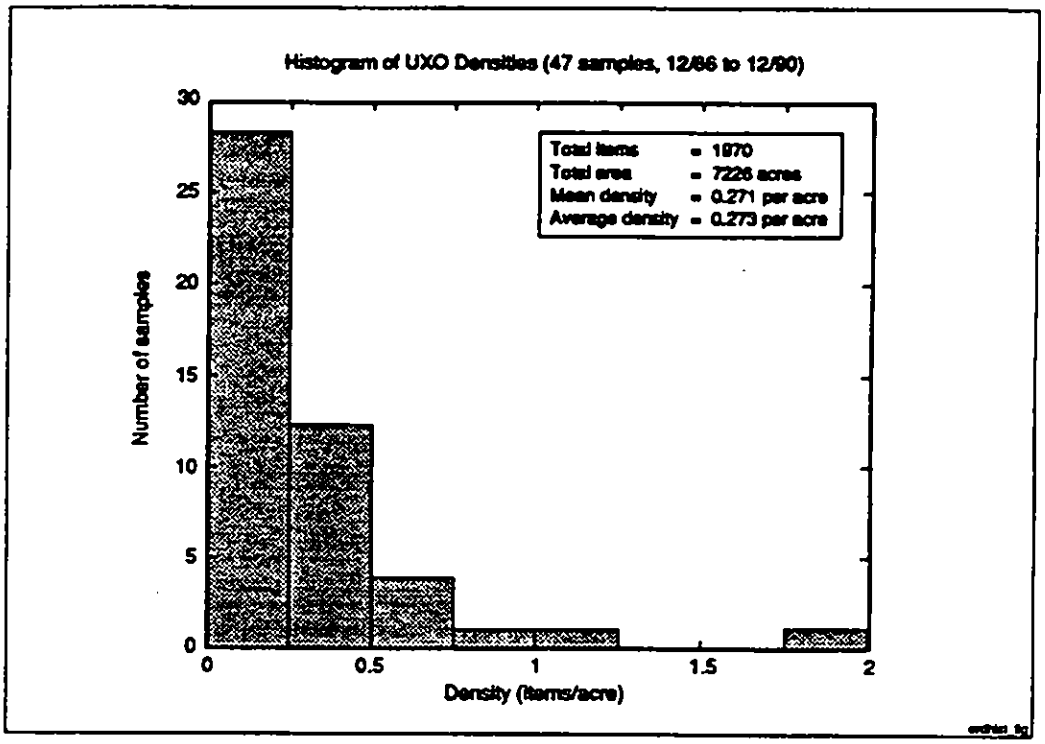

Figure 2.2: Histogram of UXO surface density data, December 1986 to December 1990. Items 20 mm and smaller are not included.

found during each quarter.[2] The largest item found during this period was a 1000-pound bomb. (A 16-inch naval gun projectile was found in July 1986.)

The item densities (that is, the number of items per acre for each of the sample areas) have been calculated from the four-year data base for items larger than 20 mm. The density data are shown in the form of a histogram in Figure 2.2. There are 47 samples represented over the study period (the period is 49 months long; clearance operations were not conducted during two of those months). The histogram displays the number of samples for which the item density lies in the given range. For example, 28 of the 47 samples have an item density lying between zero and 0.25 items per acre. The minimum density in the sample set is zero (four of 47 samples, all from the eastern portion of the

[2]Such items will not be included in the contamination estimates to be developed here. This practice was also followed by the Marinco study team.

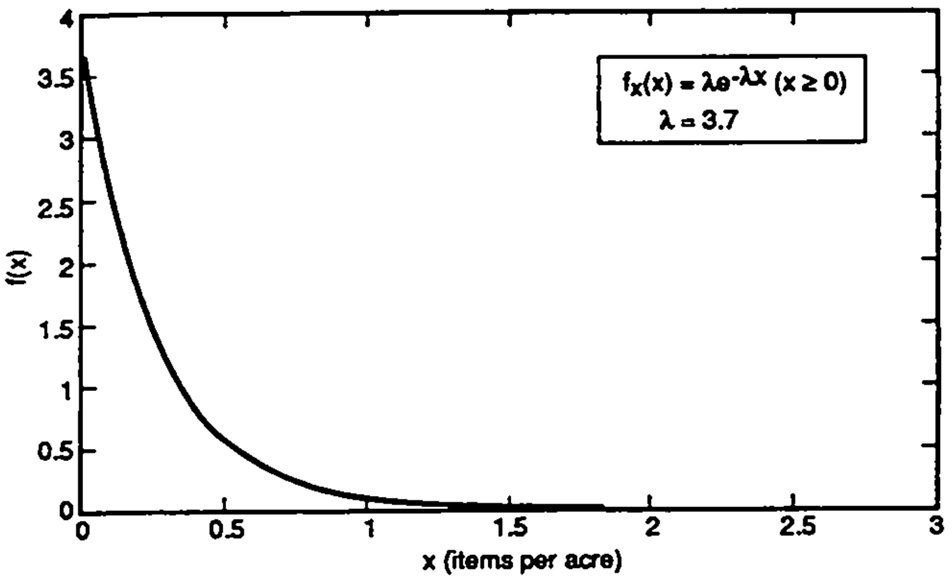

Figure 2.3: Probability density function for item density.

island); and the maximum density is 1.95 (one sample, from the Target Area). The mean of the individual densities in the data set is 0.271 items per acre; the average density (that is, the total number of items found over the four-year period divided by the total area surveyed) is 0.273 items per acre.

The histogram can be used to construct a probability density function for the item density. The Poisson probability density theoretically describes random phenomena of the type under consideration. Denoting the item density by the random variable x, we have

$$f_{\mathbf{x}}(x) = \lambda e^{-\lambda x} \quad (x \geq 0) \tag{2.1}$$

where λ is numerically equal to 3.7, the reciprocal of the average item density (0.27 items per acre). This probability density is shown plotted as a function of x in Figure 2.3. We can use this function to calculate various quantities of interest. For example:

- The probability that a randomly chosen acre of ground contains one or more ordnance items on the surface is approximately 0.025 (that is, one chance in 40).
- The most probable number of ordnance items remaining on the surface of Kaho'olawe is slightly less than 6000 (that is, the expected value per acre times the total area of Kaho'olawe in acres, less the number of items removed during the surveys).

We have also partitioned the available data into three subsets, one for each of the three regions of the island (the western Troop Safety Zone, the Target Area, and the eastern region), in order to estimate the surface contamination densities in these areas. In those sweep operations which were conducted on more than one region, we assigned half the area and half the number of items located to each region (the data do not permit any greater precision). The average densities in each region were found to be the following:

- In the Troop Safety Zone: 0.25 items per acre (about one item per four acres);
- In the Target Area: 0.43 items per acre (about one item every 2.3 acres); and
- In the region east of the Moa'ula Boundary: 0.19 items per acre (about one item every five acres).

Comparing these results with the results of the Marinco study of 1976, we note that our estimate of 0.25 items per acre in the Troop Safety Zone is seven percent less than that of the Marinco study; our estimate of 0.43 items per acre in the Target Area is 16% higher; and our estimate of 0.19 items per acre in the region east of the Moa'ula Boundary is over six times higher than the Marinco estimate. We believe that the great difference between the two estimates in the eastern region is the result of the fact that a "broad area reconnaissance" (a walking tour) of an area, as conducted by Marinco, is not sufficient to enable making accurate estimates of surface contamination density.[3] We also note that

[3]No criticism of the Marinco results should be inferred from this statement. Their efforts were concentrated in the Target Area and the Troop Safety Zone.

the data available to us come from a much larger fraction of the total area of Kaho'olawe than did the data gathered by the Marinco team. We therefore expect our density estimates to be more accurate than those based on a smaller sample of the area.

One must be careful to note that the ongoing surface-clearance efforts involve not only location but also removal of the items found. The actual densities on the ground are therefore expected to be much lower in those areas which have actually been cleared. Using an assumed search-effectiveness probability of 0.75,[4] we infer that the average surface densities in the cleared areas are approximately one-fourth of the estimated densities discussed above: that is, *in the areas which have been swept*, the surface contamination densities are likely to be approximately 0.06 items per acre in the Troop Safety Zone, 0.11 items per acre in the Target Area, and 0.05 items per acre in the eastern region. In the as yet unswept portions of each of these areas, one expects the larger surface densities estimated above.

Because clearance operations must cope with the scrap metal and inert ordnance recovered during the search for and recovery of dangerous items, we have also developed some statistics for this material. Over the four-year period we are considering, the total weight of scrap and inert ordnance collected was 615,596 pounds (over 300 tons). The average density of this material was approximately 85 pounds per acre. The amount of material yet to be removed from the island is thus expected to be over 1200 tons. A histogram of the scrap density in pounds per acre is shown in Figure 2.4. The mean of the scrap densities in the data set is 113.7 pounds per acre. The average density (that is, the total scrap weight divided by the total area) is 85.2 pounds per acre.

2.2.2 Field Inspection

The study team visited Kaho'olawe for a four-day period in February 1992. Accompanied by a military Explosive Ordnance Disposal (EOD) technician, the team investigated several different areas on the island. The principal purposes of the visit were (1) to investigate the use of magnetometry in detecting and

[4] The search-effectiveness probability (SEP) measures the fraction of items which are found during a search. This quantity typically varies between 0.5 and 0.9, depending on the terrain and the interval between searchers.

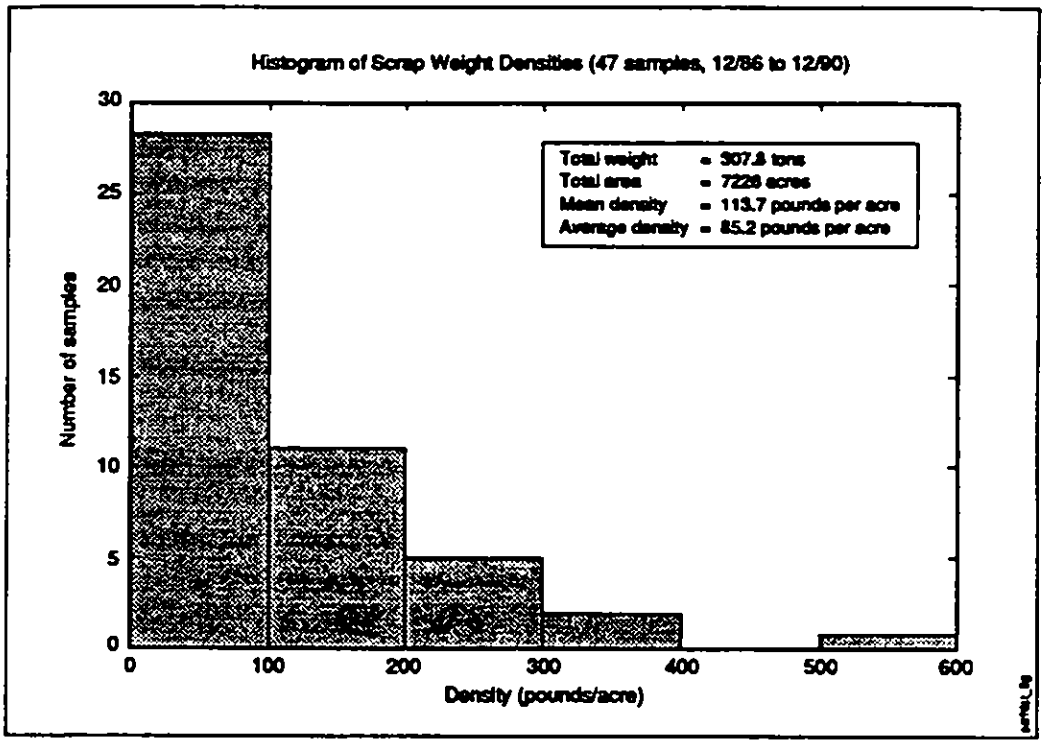

Figure 2.4: Histogram of scrap density data, December 1986 to December 1990.

locating buried ordnance; (2) to gain an appreciation for the vegetation and terrain features on Kaho'olawe; and (3) to observe at first hand the extent of visible ordnance contamination. Conducting an ordnance survey *per se* was not an objective of the field visit, but some important observations relating to ordnance contamination and clearance were made. These included:

- Except very close to the targets themselves, ordnance items are rather difficult to spot; a casual walking tour in most places on the island will yield few if any observations of surface ordnance items. A concentrated search effort is required to locate these items.

- The regrowth of vegetation in previously barren areas, particularly those near the targets themselves, appears to be proceeding rapidly. Clearance of these areas will become increasingly difficult as they become overgrown. If the decision is made to clear unexploded ordnance from Kaho'olawe, time will be of the essence: the task will be easier the sooner it is begun.

These matters are discussed more fully in Chapter 4.

2.2.3 Subsurface UXO Contamination on Kaho'olawe

When only surface sampling data are available, but when subsurface data are also desired, one can make inferences based on experience at similar sites. These inferences are, of course, only approximate, but they do constitute one means for making estimates of subsurface contamination. We have reviewed data related to the clearance of the former Camp Elliott near San Diego, California [26, 27]. TheTierrasanta Community was developed on the site in the late 1960s and opened to the public for sale in 1970. One member of the study team (Casey) visited Tierrasanta in early 1992. The terrain and vegetation resemble those on Kaho'olawe.

It was found that in the Tierrasanta project area (approximately 1900 acres) the surface contamination density ranged from 0.28 to 29.3 items per acre on the surface and from 3.0 to 90.7 items per acre in the subsurface; the subsurface contamination density is larger than the surface density, approximately by a factor of three to ten. Furthermore, it was found that approximately 87% of the contamination lay within six inches of the ground surface and that approximately 94% lay within 12 inches of the surface. We can use this information to estimate the subsurface contamination density on Kaho'olawe: we multiply the observed surface contamination densities by a factor of 5.48 (the geometric mean of 3 and 10) to obtain rough estimates of the subsurface contamination densities. Thus we determine that:

- The expected subsurface contamination density in the Troop Safety Zone lies between 0.75 and 2.5 items per acre, with a mean value of approximately 1.4 items per acre;
- The expected subsurface contamination density in the Target Area lies between 1.3 and 4.3 items per acre, with a mean value of approximately 2.4 items per acre;
- The expected subsurface contamination density in the region east of the Moa'ula Boundary lies between 0.57 and 1.9 items per acre, with a mean value of approximately 1.04 items per acre; and
- The great majority of the contamination will be found within one foot of the ground surface.

We reemphasize that these are rough estimates at best. The only way to obtain more nearly exact data for Kaho'olawe is to conduct a detailed subsurface survey.

2.3 Implications for Clearance

The estimated total densities[5] of potentially hazardous items of unexploded ordnance on Kaho'olawe are approximately one item per acre in the region east of the Moa'ula Boundary, two items per acre in the Troop Safety Zone, and three items per acre in the Target Area. This result has important implications for the approach to be followed in the clearance itself.

There exist two distinct approaches to clearance of unexploded ordnance from a given area. The first, called *area recovery*, involves excavating the soil

[5] That is, the sums of the surface and subsurface densities.

in the affected area to the required depth,[6] sifting the soil for unwanted items, and then replacing and stabilizing it. This rather drastic method of clearance, which can be very damaging to the environment, is recommended when the density of unexploded ordnance items exceeds 1000 items per acre [14]. Since the densities estimated on Kaho'olawe are less than this by nearly three orders of magnitude, we conclude that area recovery will not be required for the clearance of Kaho'olawe.

The other approach to clearance is *point recovery*, recommended for areas where the density of unexploded ordnance items is less than 1000 items per acre [14]. In point recovery, unexploded ordnance items are located and removed on an individual basis. This latter approach is clearly the method of choice for Kaho'olawe. It depends, however, on the technical capability resident in the explosive ordnance disposal (EOD) community—and in the clearance team itself—to locate unexploded ordnance items on and beneath the ground surface. Detection and location technologies are assessed in the next chapter.

2.4 Corollary HTW Considerations

Because of the ordnance which has been detonated on Kaho'olawe in the past, as well as the unexploded ordnance which yet remains there, it is possible that hazardous and toxic waste (HTW) contamination may be present in Kaho'olawe's soils. This contamination may include explosive compounds, their decomposition products, and heavy metals. Some of these materials are known to be hazardous to human health. We note, however, that such residues are far more likely to be present when explosives are burned than when they are detonated. Kaho'olawe has not been used as a site for disposal by burning of explosive materials.

An HTW survey and assessment would be necessary in order to determine the magnitude and extent (if any), and the potential consequences, of such contamination.[7] Soil samples would be collected from areas where contamination is suspected and then subjected to chemical analysis. Such a survey could

[6]The required excavation depth depends on the projected land use(s) for the area. This matter is discussed at length in Chapter 4.

[7]Hazardous and toxic waste contamination assessment and remediation planning is outside the scope of the present effort, which deals only with explosive materials and the imminent

be conducted on Kaho'olawe at any time, although it is usual that this kind of work be done after UXO clearance is complete. If an HTW survey is to be conducted on Kaho'olawe, we recommend that it be performed in conjunction with the UXO clearance project, after the sites most likely to be HTW-contaminated (that is, the former targets) have been cleared of unexploded ordnance.

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hazard associated with UXO. We include mention of the HTW issue, however, in the interest of completeness.

Chapter 3

Detection and Location of Buried UXO

O ka makapō wale no ka mea hāpapa i ka pōuli.
Only the blind grope in darkness.

Ahuwale ka nane hūnā.
The hidden answer to the riddle is seen.

It was pointed out in the previous chapter that, based on the estimated area density of ordnance contamination on Kaho'olawe, the preferred approach to the clearance of unexploded ordnance from the island will be point recovery, rather than area recovery. Point recovery depends for its success on the capabilities of technical means for the detection and location of ordnance items on, and especially beneath, the ground surface. In this chapter we review the present state of the art in detection and location technology for subsurface UXO and we discuss the new technologies which may become available to support UXO detection and location. We also discuss the physical conditions prevailing on Kaho'olawe which will affect the performance of equipment based on these technologies. We begin by considering the detection problem in general terms.

The detection of buried or otherwise concealed objects is a subject of intense interest in many areas of endeavor, including geological exploration for minerals and hydrocarbons, characterization of sites used for waste disposal, medical imaging, airport security, (explosive) mine detection, and nondestructive testing. Despite this broad interest, robust detection of buried objects is still difficult to achieve in practice, and the subject is presently under investigation by many researchers. At this time many approaches to subsurface detection have been formulated, but all such approaches suffer from several fundamental problems.

Many of the signals used to search for buried objects are partially reflected as they contact the air-earth interface. These signals may also be attenuated (diminished in amplitude) as they pass through the earth. Hence, it can be difficult to propagate a signal of adequate power to the object and back to the sensor. This situation is exacerbated for deeply buried objects, and is the principal reason for failure to detect an object which is in fact present.

In addition to the desired signals emanating from or scattered by the targets of interest, sensors receive spurious signals (noise) from various sources. Typical sources of noise include buried inhomogeneities (rocks, voids, debris) and surface clutter (vegetation, rocks, surface litter, and topographic irregularities). In certain cases the detection system may confuse these undesired signals with a target, in which case the noise signal constitutes a "false alarm". A system which incurs too many false alarms is of limited value.

In what follows, we review some of the technical issues associated with finding buried unexploded ordnance. In order to determine which technical means might be appropriate to this problem, one must address the question of how a buried bomb or artillery shell is different from the rocks and soil in which it is embedded. Some of these differences, and detection and location techniques based thereon, are discussed in the next section.

3.1 An Overview of Detection Technologies

As noted previously, detection of buried objects has been studied intensively by groups with various objectives. These investigations have produced a wide variety of detection techniques which can be considered for use in ordnance clearance operations. In this section we review the extant detection technologies and comment on their applicability to the problem of interest here. More detailed discussions of some promising techniques appear in Section 3.2.

3.1.1 Electromagnetic Techniques

The metallic casing of a bomb or gun shell is a much better electrical conductor than is rock or soil. The conductivity contrast between an item of buried ordnance and its surroundings can be exploited by several means in order to locate the item. Inductive metal detectors, for example, such as those used to locate buried metallic pipes (or coins buried in beach sand) make use of the fact that the presence of nearby metal causes a change in the inductance of a coil (typically located at the end of a long boom and held close to the ground). The change in inductance is manifested by a change in the resonance frequency of a tuned circuit; the frequency change, and thus the presence of the object, can be detected by the operator.

A detector based on this technology was recently demonstrated by the Defence Research Establishment Suffield (DRES) of Canada [28]. The device in question is designed to be towed by a vehicle moving at speeds up to 10 km/h; the sensor provides a real-time indication of buried objects. Preliminary experimental results for highly conducting metallic objects are encouraging [29].

An instrument employing a somewhat different technique to detect ferrous objects (i.e., objects made of iron) is the magnetometer. Ferrous objects cause a perturbation in the natural geomagnetic field which is detected by this instrument. Recent advances in magnetic field sensors have made these devices compact and more sensitive. Magnetometers have found several military applications, including the detection of armored vehicles and submarines. A very compact magnetometer system, capable of not only detecting but also identifying simple buried objects, has recently been demonstrated [30].

The difference in electrical conductivity also means that an electromagnetic wave will be reflected differently from a buried bomb than from, say, a rock. Thus radar techniques—in which an electromagnetic wave is sent toward a suspected target and the reflected wave observed at a receiver—can be used to detect the presence of an item. By providing electromagnetic illumination at a variety of angles and/or frequencies and observing the scattered signals, one can construct an image of the target. Novel approaches which use very wideband pulsed signals to illuminate the target have been recently developed and have shown great promise in ground-probing applications.

A large-scale demonstration of ground-probing radar was performed in 1981 when the Shuttle Imaging Radar (SIR-A) was used to image the Western Desert of Egypt and Sudan. The extreme dryness of the soil in that region[1] permits an electromagnetic signal to penetrate a meter or more of sand, and the resulting radar images revealed a surprisingly large network of ancient river channels [31]. Subsequent work with the SIR-B system in 1984 over Saudi Arabia [32] and Nevada [33], and with the Seasat radar over the Mojave Desert of California [34], has produced similar results.

As noted above, wideband radar is a promising approach to subsurface imaging. Portable ground-probing radars have been proposed to detect underground utility lines (pipes, cables, conduits, drain tiles) and a system of this type has been demonstrated by a group at the Ohio State University (see [35] for a recent review). Experimental results obtained with this system indicate that it can detect a buried pipe (a challenging target) at a depth of 30 inches. With a moderate amount of image processing, the investigators were also able to resolve rocks around the pipe and the pipe trench boundary (revealed through the difference in soil compaction) using this instrument.

Despite the considerable success of these techniques, they each have a nonzero probability of missed detections and a nonzero probability of false alarms. It has been noted that in dangerous environments these methods are often individually incapable of detecting a hazard with an acceptably high level of confidence. A recent investigation of mine detection [36] found, however, that the probability of detection could be greatly enhanced by combining information from complementary sensors. By fusing data from a ground-penetrating radar and an induction sensor, the aforementioned study achieved detection rates of roughly 90% for a mixed group of metal and plastic mines. Data fusion techniques are not limited to electromagnetic sensors: the combination of ground-penetrating radar and thermal neutron activation (to be discussed below) was suggested for further investigation in [36].

The encouraging results obtained with electromagnetic techniques makes them among the most promising of the existing detection technologies. This state of affairs arises primarily because of the large difference in the electrical properties (conductivity and permeability) of ordnance with respect to those

[1]The water content of soil has a profound effect on radar signal attenuation. Very dry soil has a small attenuation.

of the background medium (earth). Further discussion of these detection techniques appears in Section 3.2.

3.1.2 Acoustic Techniques

Because the acoustic properties of a buried bomb or shell differ from those of its surroundings, sound waves reflect differently from the items of interest than from subsurface rock. Sonar techniques—similar to radar, except that sound waves rather than electromagnetic waves are used—can therefore be employed to detect the presence, or form an image, of the target object. New approaches to this problem using wideband pulsed signals and so-called localized wave techniques are under active study. A familiar application of acoustic imaging is the use of sonography to monitor fetal development.

The mathematical basis for studies of acoustic waves is similar to that for electromagnetic waves, and some of the electromagnetic sensor concepts reviewed above have analogs in acoustics. Acoustical sensors are widely used in commercial applications at present; in some respects, these sensors are more advanced than their electromagnetic counterparts. Biomedical acoustic scanners are in common use and offer portable, near-real-time (instantaneous), imaging capability. Nondestructive testing systems with similar capabilities have also been demonstrated [37]. Geophysical prospecting using seismic methods has been ongoing for approximately 65 years; that technology is now quite advanced.

Differences in the propagation characterics of various media determine the applications of electromagnetic and acoustic sensors. For example, electromagnetic waves are rapidly attenuated by seawater, but acoustic waves propagate well in that medium. In the same manner, the interiors of conducting metal bodies, which are of interest in nondestructive testing, are more easily explored with acoustic sensors. Acoustic techniques encounter difficulties when a sudden change in the velocity of propagation occurs (generally at a discontinuity in the material density) because of reflection of the incident signal. This situation is encountered in imaging the interior of the human body: one finds that acoustical images of the abdomen are readily obtained, but the interiors of the thoracic cavity and the skull are more difficult to image. The air-earth interface is, therefore, an important consideration in the application of acoustic sensors to the buried ordnance detection problem. We remark that changes in the acoustic properties of a medium need not accompany changes in its electromagnetic properties. Hence, it is reasonable to assume that in some cases acoustic and electromagnetic sensor capabilities could be complementary.

In general, however, we find that acoustic methods are not well suited to UXO detection for two reasons. First, we observe that the difference in acoustical properties (e.g., density) of soil and ordnance are not sufficiently different to permit robust detection: native stones and ordnance both produce strong reflections of sonar signals. This situation leads to a large number of undesired detections and a concomitant loss in sensor reliability. Second, we note that strong variations in the acoustic properties of soil can arise naturally, for example as a result of different degrees of soil compaction. This situation makes it difficult to interpret the results of acoustical sensors. Finally, we note that there is no indication that a system based on acoustical methods which is capable of robust ordnance detection has ever been proposed or constructed.

3.1.3 Chemical Techniques

A buried explosive object differs from its surroundings in a very fundamental way: its chemical composition. Explosive compounds are made by providing a combustible material with an available "built-in" supply of oxygen. The most common way in which this is done is to replace certain hydrogen atoms in an organic compound with nitro groups (NO_2) containing one atom of nitrogen and two of oxygen. The presence of nitrogen is thus a key feature of most explosive compounds, and its detection can indicate the presence of such compounds. The mass fraction in explosives is typically near 20%. An example is shown in Figure 3.1, where we depict the structures of toluene and its nitrated counterpart, 2,4,6-trinitrotoluene (TNT).

In principle, one can detect the presence of chemical vapors released from an explosive using passive "sniffer" techniques. Such an approach, however, can be very difficult to use successfully in a field environment. A more attractive approach is to make the explosive reveal itself by exciting it in some way and observing the response to this excitation. Two such methods are under active investigation at the present time: electron-beam x-ray activation and neutron activation.

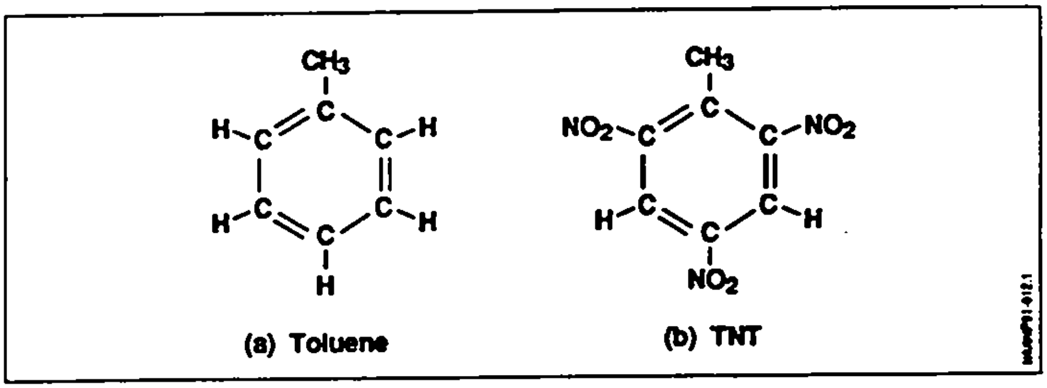

Figure 3.1: Structures of toluene and TNT.

Activation of the nitrogen in an explosive by illuminating it with x-rays produced by a high-energy beam of electrons is under study for mine detection. When the nitrogen in the explosive is excited by the x-rays, a fraction of the nitrogen is converted to a short-lived radioisotope which emits gamma rays as it decays. Detection of the characteristic gamma-ray "signature" reveals the presence of the explosive. The process is shown schematically in Figure 3.2.

In practice, it is found that successful detection of ordnance via this method is not likely. The combination of the relatively high attenuation of the radiation in soil and the thick metal shell casings, which act as shields, makes it difficult to deposit x-ray energy on the explosive charge. We note that these conclusions are not relevant to the problem of land mine detection, since mines are generally cased in wood or plastic and are buried at relatively shallow depths.

Activation using neutrons from a radioactive neutron source accomplishes a similar purpose. Neutron activation is well understood and has previously been used in the analysis of coal and minerals. Recently, an explosive detection system based on this concept has been developed for airport luggage screening [38]. Tests of these devices at the San Francisco and Los Angeles International Airports produced detection probabilities of 90 to 96 percent.

An assessment of this technology for UXO detection indicates that while it may be effective in mine detection, it is probably not an effective method of detecting buried UXO objects. One finds that thermal neutrons do not penetrate soil well, and sources of fast neutrons, with the required shielding,

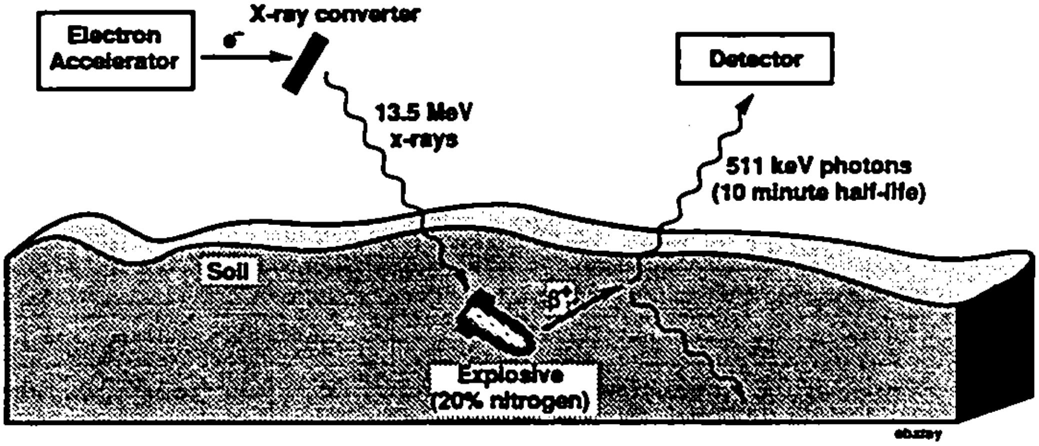

Figure 3.2: Explosive detection by electron-beam x-ray activation.

tend to be large and bulky. It is possible, however, that new developments in this technology may lead to viable systems in the future.

3.1.4 Thermal Imaging Techniques

Differences in the thermal properties of UXO and soil give rise to another potential means of detecting subsurface ordnance. The basis for this approach is the finding that all objects emit photons (quanta of electromagnetic radiation) in relation to their temperature. For example, this page, when held at room temperature, emits on the order of 10^{21} photons per second. At temperatures commonly encountered in the natural environment, this radiation is primarily in the infrared (IR) portion of the electromagnetic spectrum, but hotter objects, such as the sun at approximately 6000 K, can emit significant numbers of photons at visible wavelengths. Sensors that can detect IR radiation of a given wavelength are widely available,[2] and advanced sensor systems can produce images of the IR radiation emitted by a scene.

The presence of buried UXO distorts the normal temperature distribution in the overburden (the overlying soil). Hence, an imaging IR sensor which can measure this temperature distribution can, in principle, detect the presence and location of such an object. Unfortunately, several problems are encountered in thermal detection of buried objects. First, it is found that the number of photons emitted by a surface is proportional to a property of the surface known as *emissivity*. Differences in emissivity can arise as a result of changes in the composition of the surface, and such variations are a form of clutter for any sensor of ground temperatures.

Second, there exist several sources of IR radiation in the natural environment which are unrelated to the temperature variations of interest. These include the sun, emission from the atmosphere, and absorption and re-emission from vegetation. This radiation, when reflected by the earth, can be misinterpreted as arising from temperature variation in the soil and, hence, its presence can lead to false alarms.

Finally, the air mass between the sensor and the viewed surface absorbs and re-emits IR radiation. The effect of this process must also be accounted for in interpreting the data.

The foregoing limitations with IR sensors make it difficult to sense UXO-induced soil temperature variations, but recent work at the Lawrence Livermore National Laboratory (LLNL) suggests that by using two IR images which are acquired at different wavelengths, it may be possible to remove many of these clutter sources. An instrument based on this approach has been used to detect an underground aquifer, variations in soil properties as a result of an underground nuclear test, several archaeological artifacts, and land mines. Further discussion of this approach appears in Section 3.3.3.

[2]Many home intruder detection systems employ IR sensors to detect thermal emissions from a human body.

3.2 The Practical State of the Art

At the present time, detection methods which are based on electromagnetic signals, that is, ground-penetrating radar (GPR), magnetometry, and electromagnetic induction techniques, constitute the practical state of the art in detection and location of buried ordnance. Ground-penetrating radar is an active detection and location technique in which an electromagnetic wave is transmitted into the earth and scattered by the buried object. The scattered field is detected and used to infer the size and depth of the target. Magnetometry is the measurement of the local geomagnetic field, which is altered by the presence of a nearby ferrous object. Detection of changes in the local field is used to infer the presence of the object. Electromagnetic induction sensors can detect metallic (including non-ferrous) objects by making use of the fact that the presence of a conducting object causes a change in the resonance frequency of a nearby resonant circuit. These techniques are described in some detail in this section.[3]

3.2.1 Ground-Penetrating Radar

The term "radar" (an acronym for RAdio Detection And Ranging) applies to the use of electromagnetic waves for illumination of the target. Detection of the wave reflected by a target provides an indication of the target's presence, and measurement of the transit time of the wave from the transmitter to the target and back to the receiver allows one to estimate the range to the target.

Radar is among the most useful remote sensing techniques extant. It is employed in such diverse applications as air traffic control, aircraft and ship navigation, spacecraft docking, satellite tracking, remote sensing of the terrestrial environment, and extraterrestrial exploration.

Although the majority of radar applications involve propagation through the atmosphere, it has been known for some time that radar can also be used to detect subterranean objects. By using appropriate waveforms, antennas, and signal processing, one can obtain remarkably informative data regarding buried objects and geophysical features. Ground-penetrating radars (GPRs) are presently used in a wide variety of applications. The accomplishments of

[3]The material in this and the following sections is of necessity rather technical. The non-specialist reader may turn directly to Section 3.4.

such systems range from the detection from space of hitherto unknown geological features [31, 32, 33, 34] to routine detection of buried utility lines under city streets.

In this section we review the operation of GPR, and we assess the suitability of such a system for locating buried UXO. Our discussion begins with a review of the principles of conventional (atmospheric) radar in Section 3.2.1.1: one finds that GPR systems have much in common with conventional radars, and some familiarity with the operation of the latter is useful. In Section 3.2.1.2 we describe a GPR system, noting how such a system differs from a conventional radar. We review the topics of waveform selection, antenna design, and signal processing. The discussion emphasizes systems appropriate to the detection of relatively small objects at shallow depths (i.e., some aspects of GPR which are specific to geophysical exploration are not treated). Section 3.2.1.3 presents a review of some existing notable GPR systems.

3.2.1.1 Fundamentals of Radar Systems

The essential components of a conventional radar system are shown in Figure 3.3. In its simplest form a radar comprises (1) a transmitter, which generates an appropriate waveform; (2) an antenna, which radiates the waveform to some region of interest; (3) an antenna which receives the scattered signal; and (4) a receiver which processes the scattered waveform in order to retrieve the information of interest (e.g., the presence of a target). In many conventional radars the same antenna is used for transmission and reception. In the latter configuration, or when the receiving antenna is merely placed close to the transmitter, a so-called transmit-receive (TR) switch is used to protect the sensitive receiver electronics from the powerful transmitted signal.

The operation of this simple radar proceeds in a straightforward manner. The transmitting antenna is energized by the transmitter and produces an electromagnetic field which propagates radially outward from the antenna. Radar antennas are designed such that the radiated field is strongest in some well-defined direction of interest. In all directions the radiated field propagates as a spherical wave which diminishes in amplitude as $(4\pi r)^{-1}$ where r is the radial distance from the antenna.

The target effectively converts a very small fraction of the radiated field

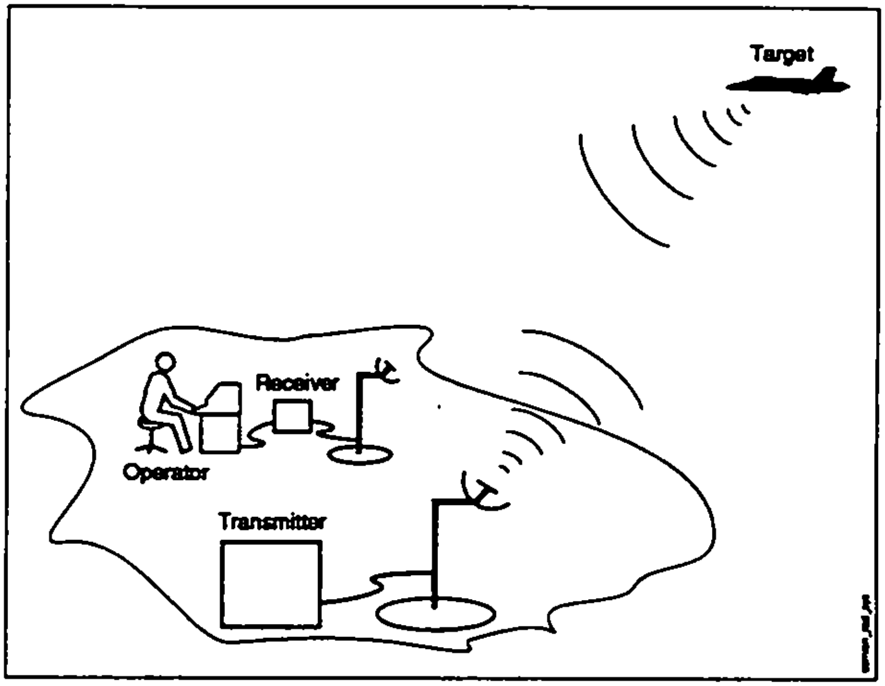

Figure 3.3: A conventional radar system.

into a field which propagates back toward the observer. The scattered field propagates back to the receiver as a spherical wave and, again, the spreading of the beam diminishes its amplitude by the factor $(4\pi r)^{-1}$.

The receiving antenna captures the scattered signal and delivers it to the receiver. There, the information in the received signal is extracted via appropriate processing. This processing can dramatically improve the detectability of the target.

It is advantageous for several reasons to operate radars in a narrowband mode. Typical radar waveforms are pulsed continuous wave (CW) signals or pulses with linear frequency modulation (FM). Denoting by f_0 and B the effective center frequency and bandwidth of the radiated waveform, narrowband operation requires $B/f_0 \ll 1$. Since the electromagnetic phenomena of propagation and scattering are linear, it follows that the received waveform is also narrowband, and a frequency-domain description of the system is appropriate.

The performance of narrowband radars is commonly described in terms of the radar range equation which we now develop. If the transmitter were used to drive an isotropic antenna, the radiated power density W_{rad} in the far field would be

$$W_{rad,iso} = \frac{P_t e^{-\beta r}}{4\pi r^2} \qquad [\mathrm{W/m^2}] \tag{3.1}$$

where β $[\mathrm{m}^{-1}]$ is the attenuation coefficient of the medium of propagation. For clear air at typical radar frequencies, β can be neglected, but precipitation can induce substantial loss at higher frequencies.

The directional characteristics of a narrowband transmitting antenna are expressed by the antenna gain $G_t(\theta,\phi)$, where (θ,ϕ) are the standard spherical coordinates. This factor defines the degree to which the antenna deviates from an isotropic radiator and allows us to write

$$W_{rad}(\theta,\phi) = \frac{P_t G_t(\theta,\phi) e^{-\beta r}}{4\pi r^2} \qquad [\mathrm{W/m^2}] \tag{3.2}$$

The power intercepted by the target and reradiated in the direction (θ',ϕ') is described by the target's scattering cross section σ $[\mathrm{m}^2]$. For a receiving antenna at the position (r',θ',ϕ') with respect to the target we write

$$W_{scat}(\theta',\phi') = \left(\frac{P_t G_t(\theta,\phi) e^{-\beta r}}{4\pi r^2}\right)\left(\frac{\sigma(\theta',\phi'|\theta,\phi) e^{-\beta r'}}{4\pi (r')^2}\right) \qquad [\mathrm{W/m^2}] \tag{3.3}$$

The ability of the receiving antenna to collect the power from the scattered waveform is expressed in terms of an effective receiving area A_r [m^2]. We write

$$P_r = \left(\frac{P_t G_t(\theta,\phi) e^{-\beta r}}{4\pi r^2}\right)\left(\frac{\sigma(\theta',\phi'|\theta,\phi) e^{-\beta r'}}{4\pi (r')^2}\right) A_r(\theta',\phi') \qquad \text{[W]} \tag{3.4}$$

The effective area of a receiving antenna can be related to the gain of the antenna G_r and the transmitted wavelength λ as follows:

$$A_r = \lambda^2 \frac{G_r}{4\pi} \tag{3.5}$$

from which we obtain the final relation

$$P_r = \frac{P_t \lambda^2 G_t(\theta,\phi) G_r(\theta',\phi') \sigma(\theta',\phi'|\theta,\phi)}{(4\pi)^3 (r')^2 r^2} e^{-\beta(r+r')} \tag{3.6}$$

In the most common case, in which the same antenna is used for transmission and reception, we have

$$P_r = \frac{P_t \lambda^2 G^2(\theta,\phi) \sigma(\theta,\phi|\theta,\phi)}{(4\pi)^3 r^4} e^{-2\beta r} \tag{3.7}$$

An important metric for radars and communication systems is the signal-to-noise ratio S/N. For such systems the noise in the received signal can be expressed in the form of thermal or Johnson-Nyquist noise. We write the noise power σ_{nn}^2 as follows:

$$\sigma_{nn}^2 = KTB \tag{3.8}$$

where $K = 1.38 \times 10^{-23}$ [J/K] is Boltzmann's constant, and T [K] is the effective noise temperature. The receiver temperature is commonly related to a standard temperature T_0 (taken to be 290 K by convention) via a noise figure F. We write

$$\sigma_{nn}^2 = KT_0BF \tag{3.9}$$

Using this result we obtain the following expression for S/N:

$$S/N = \frac{P_r}{\sigma_{nn}^2} = \left(\frac{1}{KT_0BF}\right)\left(\frac{P_t \lambda^2 G^2(\theta,\phi) \sigma(\theta,\phi|\theta,\phi)}{(4\pi)^3 r^4}\right) e^{-2\beta r} \tag{3.10}$$

An important receiver processing technique is the matched filter. One can show that when used with an appropriate thresholding operation, the matched filter comprises the best linear processor for a system designed to perform detection. The signal produced by this filter is the correlation of the received waveform with the transmitted waveform and, as such, it is useful to define a variable t_P at the decorrelation time of the transmitted waveform. In general we have

$$t_P B \approx 1 \tag{3.11}$$

It is well known that the matched filter optimizes the signal-to-noise ratio. One can show that the degree of S/N improvement as a result of matched filtering is given by the time-bandwidth product $T_P B$ where T_P is the duration of the waveform (typically $t_P \leq T_P$). The use of chirped pulses, which have a larger bandwidth than a CW pulse, is motivated in large part by a desire to increase $T_P B$.

The duration of the radar pulse T_P and the pulse repetition frequency (PRF) have important roles in determining the radar's performance. For a general receiver, the pulse length specifies the resolution in range ρ_r as follows:

$$\rho_r = \frac{cT_P}{2} \tag{3.12}$$

where c is the speed of light in the medium of propagation ($c \approx 3 \times 10^8$ m/s in air). For a system which employs matched filtering, t_P should be substituted for T_P in the above expression with the result

$$\rho_r \approx \frac{c}{2B} \tag{3.13}$$

Hence, the use of larger absolute bandwidths B leads to better resolution.

The target's position in range is determined in a similar manner. The time t required for the radar pulse to travel to a target at range r and back is

$$t = \frac{2r}{c} \tag{3.14}$$

By measuring the time between the transmitted and received signals one can establish the distance r. For co-located receivers and transmitters, the need to disable the receiver during transmission implies that the minimum distance which can be measured is on the order of the duration of the pulse. We have

$$r_{min} \approx \frac{cT_P}{2} \tag{3.15}$$

The greatest range that can be measured is related to the PRF. The scattered pulse must be received before a new pulse is emitted. If not, the range becomes ambiguous, i.e., it is not possible to determine which pulse gave rise to the received signal. If τ is the pulse repetition interval, then the maximum unambiguous range is given by

$$r_{max} = \frac{c\tau}{2} \tag{3.16}$$

The ambiguity problem can be alleviated to a degree by coding the transmitted pulses such that the scattered signal from successive pulses can be discriminated, but we will not consider these more sophisticated processing techniques in the present discussion.

Resolution in the cross-range direction is limited by the transverse dimensions of the antenna. A uniformly illuminated circular aperture of diameter D rise to a beam whose first nulls are located at angles θ_B where

$$\theta_B = \sin^{-1}\left(\frac{3.83}{\pi}\frac{\lambda}{D}\right) \tag{3.17}$$

For electrically large apertures (i.e., $D/\lambda \gg 1$), which is the case most often employed in practice, we have $\theta_B \approx \lambda/D$. For rectangular apertures, a similar expression holds if we substitute for D the linear dimension of the aperture. Thus, the effective cross-range resolution ρ_{cr} of the antenna is given by

$$\rho_{cr} \sim \frac{r\lambda}{D} \tag{3.18}$$

It follows that to obtain good resolution in the cross-range dimension one uses smaller wavelengths λ or larger antenna apertures D. An effective alternative method of achieving larger apertures is to move a single antenna along a path in the cross range dimension, and to sum coherently the signals backscattered at different points along its path. This is the basis of the synthetic aperture radar (SAR). Surprisingly, one can show that for such a radar, the resolution in the dimension parallel to the antenna's track is on the order of the dimension of the antenna (i.e., smaller antenna dimensions in the along-track dimension lead to better resolution). Since only the relative motion of the target and observer is important in achieving this performance, and since only cross-range motion is relevant, it is possible to achieve similar high-resolution performance by illuminating a rotating target. The latter technique is known as inverse synthetic aperture radar (ISAR).

Clutter is an important concern in many radar systems. For systems which are intended to probe objects on the earth, over the sea, or in precipitation, the unavoidable illumination of regions near the target (background) leads to a scattered signal which must be separated from the desired target signature. In the detection of airborne targets, motion of the object gives rise to a Doppler shift in its scattered signal which can be used to distinguish the target from the clutter. When the object of interest is not moving relative to the clutter background, however, the problem can be much more complicated. In such cases it is advantageous to resort to higher resolution, in which case the background scattering is decreased with respect to the target signature. Alternatively, the signatures of some targets can be enhanced with respect to the background by using illumination at a particular frequency or polarization. In general, however, detection of radar signals in strong clutter environments remains a challenging technical problem.

As noted above, the waveforms emitted by most existing radars are relatively narrowband. The center frequency of these systems is a parameter which can be varied to enhance the performance of the system. The selection of a radar's frequency is influenced by many factors which include (1) the size of the targets of interest, (2) the desired resolution, (3) the physical characteristics (size, weight, transmitter efficiency, antenna gain, etc.) of microwave components for a given frequency regime, (4) the presence of generally increasing atmospheric absorption for frequencies substantially above 10 GHz, and (5) the existence of other propagation phenomena in specific problems of interest. A discussion of these issues is beyond the scope of this brief review, but we note that some of the more common operating frequencies are L and S bands (1-2 and 2-4 GHz respectively) for long-range land-based air surveillance systems and C and X bands (4-8 and 8-12.5 GHz) for tracking, navigation, and instrumentation [39, ch. 1].

3.2.1.2 Fundamental Aspects of Ground Penetrating Radars

A radar designed to probe subsurface features operates in much the same manner as the conventional radar described in the preceding section. A transmitter energizes an antenna directed into the earth. The signal scattered by a buried object or a geophysical feature is received by another antenna and subsequently processed by a receiver to extract information. The performance of such systems is governed by physical laws similar to those used in deriving the radar range equation.

While conventional and ground-penetrating radars are similar in function, they are considerably different in implementation. There are two fundamental aspects of GPR sensing which lead to these differences.

First, the effects of the medium of propagation, which are generally negligible for atmospheric radars, play a dominant role in GPR design. Attenuation of the radar signal by the lossy earth is the primary consideration in determining the range of these systems. In addition, the presence of natural subsurface inhomogeneities leads to a large amount of clutter. One often finds that the effects of this clutter dominate the random fluctuations introduced by receiver noise.

The second major difference between atmospheric and ground penetrating radars is the distances involved. The ranges and target dimensions involved in GPR are much smaller than those encountered in conventional radars. Typical ranges for GPR detection are at most a few meters, and the target dimensions of interest are typically much less than a meter. Short range operation requires (1) very short pulses, or pulses which can be separated through processing and (2) closely spaced transmitting and receiving antennas, which in turn requires better isolation of receiver and transmitter. Accurate localization of small targets requires higher resolution which can be obtained with increased bandwidth via, for example, the use of shorter pulses.

In the remainder of this section we discuss the effects of these requirements on GPR systems. We describe the effects of propagation through the earth, considerations in GPR antenna design, and the types of signal processing employed in such systems.

Subsurface Propagation Phenomena As discussed in subsection 3.2.1.1, electromagnetic fields propagate with negligible attenuation in air, and the amplitude of the signal is diminished as the inverse square of the distance (spherical wave propagation). The physics which govern the propagation of signals through earth are similar, but one must also take into account (1) the effects of attenuation, (2) coupling through the air-earth interface, and (3) the presence of conduction currents in the soil.

It is possible to describe some of the important aspects of this subject by considering the fields radiated by a dipole in an infinite homogeneous lossy medium [40]. We find that the fields radiated by a dipole with current moment $I\,dl$ are given by

$$E_\theta = \frac{I\,dl}{4\pi(\sigma + i\omega\epsilon)}\frac{\sin\theta}{r^3}\left(1 + \gamma r + \gamma^2 r^2\right)e^{-\gamma r} \tag{3.19}$$

$$E_r = \frac{I\,dl}{2\pi(\sigma + i\omega\epsilon)}\frac{\cos\theta}{r^3}(1 + \gamma r)\,e^{-\gamma r} \tag{3.20}$$

$$H_\phi = \frac{I\,dl}{4\pi}\frac{\sin\theta}{r^2}(1 + \gamma r)\,e^{-\gamma r} \tag{3.21}$$

where ω [rad/s] is the radian frequency, σ [mho/m] is the medium's conductivity, ϵ [Farad/m] is the medium's permittivity, θ is the usual angle in spherical coordinates defined with respect to the dipole axis, and

$$\gamma = i\frac{\omega}{c}\left[1 - i\frac{\sigma}{\omega\epsilon}\right]^{1/2} \tag{3.22}$$

in which $c = 1/\sqrt{\mu\epsilon}$ is the velocity of propagation in the medium. Typical soils have permeabilities μ [Henry/m] which do not deviate significantly from the free space value. The time convention $e^{+i\omega t}$ is suppressed in these results.

In the static limit ($\omega \rightarrow 0$) these fields degenerate to those due to the conduction currents alone. We have, for example,

$$E_{\theta 0} = \frac{I\,dl}{4\pi\sigma}\frac{\sin\theta}{r^3} \tag{3.23}$$

It is instructive to consider the ratio of the general case to the static limit. Following Gabillard et al. [40], we define the following quantities

$$e_\theta = \frac{E_\theta}{E_{\theta 0}} = \frac{1}{1 + i\omega\epsilon/\sigma}\left(1 + \gamma r + \gamma^2 r^2\right)e^{-\gamma r} \tag{3.24}$$

$$e_r = \frac{E_r}{E_{r0}} = \frac{1}{1 + i\omega\epsilon/\sigma}(1 + \gamma r)\, e^{-\gamma r} \tag{3.25}$$

$$h_\phi = \frac{H_\phi}{H_{\phi 0}} = \frac{1}{1 + i\omega\epsilon/\sigma}(1 + \gamma r)\, e^{-\gamma r} \tag{3.26}$$

These field ratios can now be expressed in terms of normalized quantities. We define a characteristic frequency f_c for the medium as follows

$$f_c \equiv \frac{\sigma}{2\pi\epsilon} \tag{3.27}$$

which is the frequency at which the displacement current becomes equal to the conduction current. It is useful to normalize the frequency of excitation with respect to f_c and we write

$$\beta \equiv \frac{f}{f_c} \tag{3.28}$$

In terms of this quantity, the propagation factor γ can be written

$$\gamma = \frac{2}{L_c}\sqrt{i\beta(1 + i\beta)} \tag{3.29}$$

where L_c is a characteristic length defined as follows:

$$L_c = \frac{2}{\sigma}\sqrt{\frac{\epsilon}{\mu}} \tag{3.30}$$

The characteristic frequency and length of the medium are related by

$$\pi f_c L_c = c \tag{3.31}$$

where $c = 1/\sqrt{\epsilon\mu}$ is the speed of light in the medium. We can also define a characteristic wavelength for the medium, given by $\lambda_c = c/f_c$. We find

$$\lambda_c = \pi L_c \tag{3.32}$$

Writing the propagation constant in the form

$$\gamma = \frac{1}{L_c}(a + ib) \tag{3.33}$$

where

$$a = \left(2\beta\left[\sqrt{1+\beta^2}-\beta\right]\right)^{1/2} \quad (3.34)$$

$$b = \left(2\beta\left[\sqrt{1+\beta^2}+\beta\right]\right)^{1/2} \quad (3.35)$$

and defining a normalized distance

$$x = \frac{r}{L_c} \quad (3.36)$$

we can show that the field ratios are given by

$$e_\theta = \frac{1}{1+i\beta}\left[1+(a+ib)x+4x^2\beta(i-\beta)\right]e^{-(a+ib)x} \quad (3.37)$$

$$e_r = \frac{1}{1+i\beta}\left[1+(a+ib)x\right]e^{-(a+ib)x} \quad (3.38)$$

$$h_\phi = \left[1+(a+ib)x\right]e^{-(a+ib)x} \quad (3.39)$$

Insight into the nature of subsurface propagation can be obtained from these simple relations. A plot of $|e_\theta|$ is given in Figure 3.4 for the simple case when σ, ϵ, and μ do not vary with frequency. One finds that $|e_\theta|$ is approximately unity for frequencies well below f_c, and that this ratio exceeds unity for frequencies well above f_c. In the former regime, which has been referred to as the low-frequency window (LFW), conduction currents dominate. Measurements of the ground in this regime yield primarily an estimate of the local soil impedance. In the high frequency regime, displacement currents dominate conduction currents and the medium becomes somewhat more transparent to the waves. The frequency regime over which displacement currents dominate has been referred to as the "high-frequency window" and is strongly influenced by the frequency dependence of the soil parameters.

A more realistic estimate of soil properties is necessary to estimate practical GPR performance. A number of models for these properties have been proposed. In this work we make use of a model developed by Messier [41] for wideband electromagnetic phenomena. We write

$$\epsilon(\omega) = \epsilon_\infty\left[1+\sqrt{\frac{2\sigma_0}{\omega\epsilon_\infty}}\right] \quad (3.40)$$

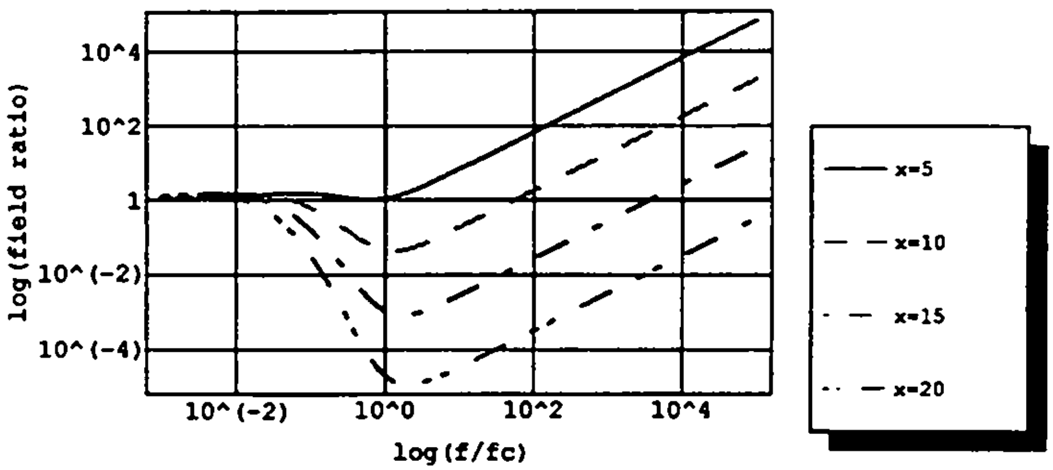

Figure 3.4: Normalized propagation characteristics of the E_θ field of a dipole in an infinite lossy medium.

$$\sigma(\omega) \;=\; \sigma_0\left[1+\sqrt{\frac{2\omega\epsilon_\infty}{\sigma_0}}\right] \tag{3.41}$$

where σ_0 is the low-frequency limit of the conductivity and ϵ_∞ is the high-frequency limit of the permittivity. Typical values are $\sigma_0 = 0.001$ to 0.1 mho/m and $\epsilon_\infty/\epsilon_0 = 4$ to 8 where $\epsilon_0 \approx 8.854\times10^{-12}$ Farad/m is the permittivity of free space. Using this model one finds that if $\omega > \sigma_0/\epsilon_\infty$, then $f/f_c \sim \sqrt{\omega\epsilon_\infty/(2\sigma_0)}$, while for $\omega < \sigma_0/\epsilon_\infty$ one obtains the result $f/f_c \sim \sqrt{2\omega\epsilon_\infty/\sigma_0}$.

A plot of the normalized propagation characteristics for this soil model appears in Figure 3.5. In this result we have assumed $\epsilon_\infty/\epsilon_0 = 8$ and $\sigma_0 = 0.01$ mho/m, whence $f/f_c \sim 0.21\sqrt{f}$ where f is expressed in MHz. We find that for short distances a GPR can successfully operate in the LFW for frequencies up to about one GHz. This modeling result is partially confirmed by the finding that the extant GPR systems operate primarily in this frequency regime. The fact that these fields diminish as $(4\pi r^3)^{-1}$, rather than with the $(4\pi r)^{-1}$ behavior seen in atmospheric radars, leads to the conclusion that fields radiated by GPRs will have very short ranges.

The penetration of signals in the LFW can also be expressed in terms of the

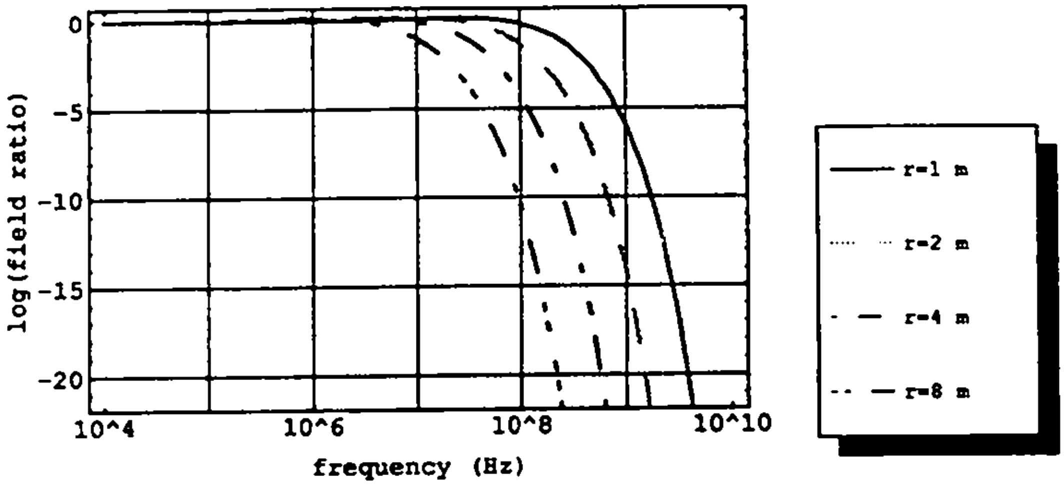

Figure 3.5: Normalized propagation characteristics of the E_θ field of a dipole in an infinite lossy medium with frequency-dependent soil parameters.

skin depth δ defined by

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \tag{3.42}$$

A short calculation reveals the relation[4]

$$\frac{r}{\delta} \approx 3.85 \Longrightarrow |e_\theta|^2 = \frac{1}{2} \tag{3.43}$$

A few numerical examples will serve to illustrate the ranges of relevance to GPR work. For a signal at 10 MHz, the effective conductivity predicted by the Messier model is approximately $\sigma = 0.02$ mho/m which leads to the distance $3.85\delta = 4.3$ m. For signals at 100 MHz the conductivity and effective distance are 0.04 mho/m and one meter respectively. At one GHz we find $\sigma = 0.1$ mho/m and $3.85\delta = 20$ cm. It is evident from these simple calculations that fields at lower frequencies have a much greater depth of penetration.

Using the results of subsection 3.2.1.1, the range resolution ρ_r of a radar of

[4]One should note that the range r satisfying this relation is not necessarily indicative of the depth of penetration of a GPR signal since coupling of this GPR waveform (launched in air) to the earth has not yet been addressed.

bandwidth Δf in soil of permittivity ϵ and permeability μ is found to be

$$\rho_r \approx \frac{1}{2\Delta f\sqrt{\mu\Re(\epsilon)}} \tag{3.44}$$

In this result it is important to note that Δf is the bandwidth in the received signal, and not the bandwidth of the transmitted waveform. For the soil model noted above, this result indicates that bandwidths on the order of several hundred megahertz are required to resolve UXO sized objects (say ρ_r =10 cm). It follows that practical GPR systems for UXO detection must have relative bandwidths approaching unity, to achieve both good penetration and good resolution.

Interface Effects The foregoing discussion does not address the effects of the air-earth interface on coupling of the source to the earth and subsequent propagation of the underground signals. The interface represents a large impedance mismatch to waves propagating into the ground, which leads to a high reflection coefficient. These effects can be rigorously incorporated through the use of Sommerfeld's spectral representation for the fields. The resulting expressions for the propagation characteristics are unavoidably complicated in this case (cf. [42, §4.9]). Fortunately, many of the important aspects of this theory can be described without recourse to this more complicated formalism, and a review of these aspects is presented below.

The primary effect of the air-earth interface is partial reflection of the incident wave. For observers which are not too close to the earth we can show

$$\vec{E}_{refl} = e^{-ik\Delta r_0}\left[R_\perp\hat{t}\hat{t} + R_\parallel\left(\mathrm{I} - \hat{t}\hat{t}\right)\right]\cdot\vec{E}_{in}(\hat{k}') \tag{3.45}$$

where $k = \omega/c$ and $\hat{t}$ and $\hat{k}'$ define the normal to the plane of incidence and the direction of the reflected wave respectively. We have

$$\hat{t} = \frac{\hat{n}\times\hat{k}'}{|\hat{n}\times\hat{k}'|} \tag{3.46}$$

$$\hat{k}' = \hat{k} - 2\left(\hat{n}\cdot\hat{k}\right)\hat{n} \tag{3.47}$$

in which $\hat{n}$ is the surface normal. The quantities $R_\parallel$ and $R_\perp$ are the Fresnel reflection coefficients for polarizations parallel to and perpendicular to the plane of incidence, viz:

$$R_{\|} = \frac{\kappa \sin\psi - \sqrt{\kappa - \cos^2\psi}}{\kappa \sin\psi + \sqrt{\kappa - \cos^2\psi}} \tag{3.48}$$

$$R_{\perp} = \frac{\sin\psi - \sqrt{\kappa - \cos^2\psi}}{\sin\psi + \sqrt{\kappa - \cos^2\psi}} \tag{3.49}$$

where ψ is the elevation angle of the reflected wave

$$\psi = \sin^{-1}(\hat{k}' \cdot \hat{n}) = -\sin^{-1}(\hat{k} \cdot \hat{n}) \tag{3.50}$$

and

$$\kappa = \epsilon/\epsilon_0 - i\sigma/(\omega\epsilon_0) \tag{3.51}$$

The additional propagation distance incurred by the reflected wave is given by

$$\Delta r_0 = \sqrt{r_0^2 + 2h_r(2h_t + h_r)} - r_0 \tag{3.52}$$

where h_r and h_t are the elevations of the receiving and transmitting antennas and r_0 is the separation between these antennas.

An illustration of these results is now presented. For colocated source and receiver which view the earth at normal incidence, we have $r_0 = 0$ and $-\hat{k} = \hat{k}' = \hat{n}$. We also find $\psi = \pi/2$ in this case which leads to the following expressions for the reflection coefficients:

$$-R_{\|}(\psi = \pi/2) = R_{\perp}(\psi = \pi/2) = \frac{1 - \sqrt{\kappa}}{1 + \sqrt{\kappa}} \tag{3.53}$$

The expression for the reflected field in this geometry degenerates to

$$\vec{E}_{refl} = e^{-i2kh}\vec{E}_{in}(\hat{k}')\frac{1 - \sqrt{\kappa}}{1 + \sqrt{\kappa}} \tag{3.54}$$

where $h = h_r = h_t$.

The fractional portion of the field transmitted across the interface is plotted in Figure 3.6 for the frequency-dependent soil parameters presented above. We observe that the transmitted field amplitude is small over the range of frequencies of interest in GPR. It should be noted that antennas located very close to

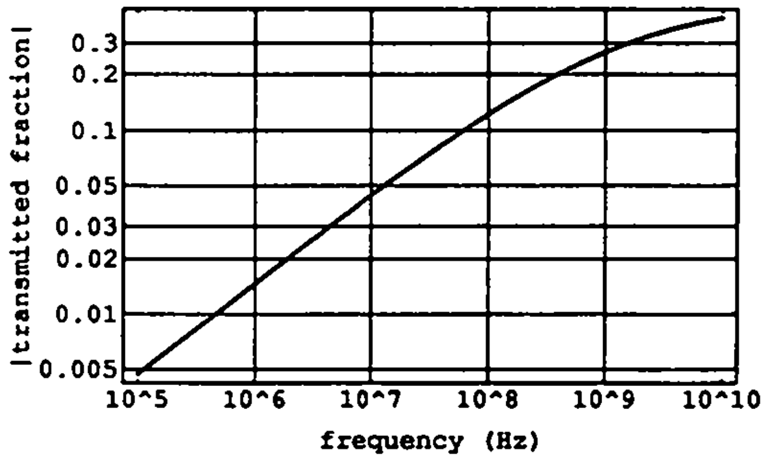

Figure 3.6: The fraction of an incident field transmitted across a planar interface.

the interface couple to the earth in a manner much different from that indicated here. The analysis of these antennas requires the Sommerfeld formulation discussed above and will not be treated here.

It follows from the preceding arguments that the amplitude of the surface reflected wave will be approximately equal to that of the transmitted wave. Hence, to protect its sensitive electronics, the receiver must be blanked during the arrival of the reflected signal. The return from a buried object at depth d will commence at a time $t_0 = 2d\sqrt{\mu\epsilon}$ after the reflected signal has passed. It follows that the duration of the transmitted signal (or its decorrelation time if a matched filter is used) establishes a lower bound on the depth of the objects which can be detected by a GPR. The total time interval for GPR signal acquisition is quite small. For an object buried at a depth d [m] in a medium with a relative permittivity ϵ_r we find

$$\Delta t \approx 6.7d\sqrt{\epsilon_r} \qquad [\text{ns}] \tag{3.55}$$

By way of example, the signal from an object at $d = 1$ m in a medium with $\epsilon_r = 9$ will be delayed by $\Delta t \approx 20$ ns.

Waveforms for GPR In the preceding discussion it was shown that the waveforms of interest in GPR must exhibit a large relative bandwidth to obtain the required resolution and propagation characteristics. This requirement imposes significant constraints on the waveforms and processing employed in GPR systems. At this time three approaches to the implementation of such systems have evolved [43].

The first approach utilizes a sinusoidal pulse whose frequency is linearly modulated with time across the desired frequency range. The received signal has a similar frequency modulation but a small delay in time. Two types of processing for such signals can be defined on the basis of the relative rates of frequency modulation. Slowly modulated (so-called FMCW) signals, for which the modulation time is large compared to the round trip time to the body, can be detected by mixing the transmitted and received signals to generate a signal at a difference frequency f_d. It is straightforward to show that f_d is directly proportional to the target's depth [44, 45]. If the signal is sampled and its spectrum computed numerically, one finds that the spectral peak can be used to infer the depth of the target, and a large increase in signal-to-noise ratio is obtained. A discrete (stepped) modulation of the frequency has also been used [46].

When the rate of modulation is more rapid, one obtains a waveform for which it is practical to use so-called time-domain "pulse compression" techniques. Signals of this type permit the use of lower peak powers than would be required for a CW pulse, and they simultaneously obtain acceptable range resolution. The matched filter response to this waveform (the correlation function) has a narrow width in the time domain which leads to the designation "pulse compression" for the filter action. It is interesting to note that this pulse compression technique is a time-domain dual to the frequency domain processing in FMCW GPRs.

The second approach to GPR implementation utilizes an impulsive waveform whose duration is at most a few nanoseconds. The spectrum of such a waveform typically contains energy well beyond the regime of effective propagation in the earth, and the signal scattered by the buried target will be effectively low-pass filtered by its propagation. The high-frequency energy in the pulse, which would seem to be unnecessary since it is not propagated to the target, is essential for "sharpening" the transmitted pulse: it produces the required "clear time" which permits effective detection in range. Systems based on impulsive waveforms have the advantage of requiring somewhat less signal processing, since the sampled time-domain waveform can be displayed and (with experience) interpreted by the operator. The principal limitations of these systems result from the need for extreme timing stability. Advantages in size, weight and cost have also been suggested [43]. An early system based on impulse waveforms was demonstrated by Moffatt and Puskar for geophysical applications [47]. Later work by Young [35, 48], and Burrell [49] at Ohio State University built on this work, and there have been subsequent improvements in systems of this type [50].

Finally, CW waveforms have been used in a limited number of GPR systems to generate microwave holograms. The primary motivation for this work appears to be early results by Anderson and coworkers (cf. [51, 52] and the more recent discussion in [53]). A related method is described by Yue et al. [54]. The use of CW waveforms in these methods provides good resolution in the horizontal dimension, but the limited bandwidth yields poor resolution in the vertical dimension, and later investigations (described below) use wideband synthetic aperture approaches to obtain true three-dimensional imaging capability.

Antennas for GPR The constraints of large relative bandwidth and low frequencies pose a challenge to the designers of antennas for GPR systems. Such antennas must be able to transmit and receive wideband waveforms, and they must be able to couple energy into the earth with some degree of efficiency. Because GPR antennas are often positioned close to the interface in order to maximize coupling, one must include the effect of the interface in calculating the radiation pattern. Finally, practical considerations often require that the antennas be relatively compact—a requirement which often leads to poor efficiency.

Existing antennas for GPR can be classified as elemental radiators (e.g., loops, dipoles, and bicones), traveling wave antennas, frequency independent antennas (e.g., self-complementary structures), and aperture antennas (especially the TEM horn). A brief discussion of these antenna types follows.

The use of elemental radiators has met with considerable success in GPR systems. These antennas are small by nature and they have electromagnetic properties whose frequency dependence can be controlled. Unfortunately, they also have low gains and low efficiencies. An interesting use of such antennas is encountered in an early Ohio State University (OSU) GPR system [35]. The OSU system employs two folded, orthogonally oriented dipoles of length 0.6 m. The use of orthogonal polarizations in GPR antennas has a number of advantages. Since it is well known that orthogonal dipoles do not couple, the system can be implemented without a TR switch, and the antenna geometry permits the transmitter and receiver to be closely spaced, thus producing compact antennas. In addition, it can be shown that orthogonally polarized linear antennas situated in a plane parallel to the air-earth interface do not respond to reflections from plane stratified media (no cross polarized component is generated in scattering from such media). This leads to improved clutter rejection for these antennas. The OSU system radiates pulses of duration 150 ps (3-dB width) with a peak drive voltage of approximately 1 kV. The bandwidth of this pulse is essentially constant out to nearly 3 GHz. The bandpass characteristics of the dipoles (which are normally narrowband devices) are enhanced by loading the elements. Since conduction currents dominate in the low-frequency window, coupling of the radiated waveform is maximized by placing the uninsulated crossed dipoles in contact with the earth. While these electrically small antennas are low-gain radiators, the large dielectric constant of the ground also helps to intensify the field in the lower half space. An improved frequency response is obtained by using a bow-tie antenna (a planar version of the bicone).

Traveling-wave antennas are a means of obtaining higher directivity with large bandwidth. Some antennas of interest include the "V-dipole" pair and the helical antenna. The latter is of considerable interest because it is compact and permits transmitter-receiver coupling to be minimized through the use of antennas with opposite polarization.

When the shape of an antenna can be specified entirely in terms of angles, its impedance and pattern are frequency independent [55, §§15.2-4]. In practice, however, there are upper and lower limits on the size of the antenna structure, and these determine, respectively, the lower and upper bounds on the frequency regime over which frequency-independent operation can be achieved. When the shape of the device is self-complementary, one can show that the impedance of the structure will be equal to half the free-space impedance $Z_0 \approx 377\ \Omega$. Common examples of these antennas include planar and conical spirals. The planar spirals are of special interest when compact, surface-conforming elements are required, but such antennas have very limited gain.

The use of aperture antennas permits one to employ higher power levels while achieving substantial directivity. Radiation of a wideband pulse from an aperture is possible with the so-called TEM horn, a device which employs traveling-wave concepts in its operation. Small TEM horns can be used as feeds for larger parabolic reflectors to obtain higher gain (and therefore, better horizontal resolution). Examples of the latter configuration are discussed by Clarricoats [44].

Signal Processing for GPR Data In its simplest form the GPR produces a signal which is proportional to the scattering properties of the medium as a function of depth. Buried objects are treated as a perturbation of the soil's scattering properties in this interpretation. (Some processing of the received signal, which we described in subsection 3.2.1.2, may be necessary to obtain these depth profiles.) By varying the orientation and position of the transmitting and receiving antenna, one can also obtain information on the horizontal distribution of these scattering properties as well. In most cases, however, it is desirable to further process the signals obtained by the radar. The motivation for such processing generally includes one or more of the following factors:

First, we note that wideband antennas frequently have poor directivity and, hence, the horizontal resolution obtained by these radars is limited. As we describe below, signal processing techniques can be used to improve the horizontal resolution of GPRs, although the usefulness of such a system in rough terrain may be somewhat limited.

Second, we note that raw GPR data, which consists of range profiles as a function of horizontal position, can be difficult to interpret. The lack of adequate cross-range resolution noted above leads to one form of difficulty in interpretation which can be illustrated by a simple calculation. The GPR response at a horizontal position (x, y) to a point target at horizontal position $(0,0)$ and depth d will have a time delay given by

$$(c\Delta t) = \sqrt{x^2 + y^2 + d^2} \qquad (3.56)$$

when this delay is plotted as a function of the horizontal coordinates, a downward pointing hyperboloid is obtained. For an antenna which is directed normal to the interface, this response will have a maximum amplitude directly over the target. As the antenna is moved away from the target's centerline, the response grows weaker because of the increased propagation distance and directivity in the antenna pattern. When sufficient data are available, an experienced GPR operator will recognize these hyperboloids and will be able to estimate the location of the buried body. The accuracy of this estimate will depend upon several factors including the local homogeneity of the soil, the strength of the signal, and the shape of the target. When limited data are available, such as one would acquire by making only isolated measurements of the surface response, the depth and location of the object are more difficult to estimate. In essence, GPR data take the form of a three-dimensional "image", but, unfortunately, because of the poor signal localization noted above and variations in the earth's electrical properties, the coordinates of this "image" data do not correspond to physical spatial coordinates.

Finally, we note that GPRs operate in a clutter-rich environment. The targets of interest may be masked by returns from surface objects or geophysical features. Signal processing permits the clutter signal to be decreased to a degree.

Simple processing is employed in almost all GPR systems. The techniques of multiple-pulse averaging to remove noise, range-gating to remove the reflection from the interface, and multiple location averaging are widely used.

More sophisticated processing can improve the effective horizontal resolution and make the data easier to interpret. A signal processing technique which accomplishes these goals while simultaneously improving the signal-to-noise ratio of the return is the generation of a synthetic aperture. Extensive exploration of this topic has been provided by Osumi and Ueno in a series of papers [56, 57, 58] but, unfortunately, a detailed discussion of this subject is beyond the scope of the present report.

Most GPR systems are employed as a precursor to excavation work. Because of the time and expense involved in excavation, it is highly desirable to minimize inadvertent detection of objects. The potential for inadvertent detection is quite high in GPR work, because of the presence of large numbers of inhomogeneities in soil (rocks, voids, and other geophysical features).

The need to discriminate against unwanted detections is well known in applications such as mine detection, where the size and shape of the target are similar to those of natural artifacts (e.g., buried stones and organic matter). One means of recognizing buried targets is via high-resolution imagery obtained through synthetic aperture processing. It appears, however, that this approach has not been explored to date.

A group at the Ohio State University has investigated the potential for automatic recognition of buried objects via the objects' characteristic resonances. Their approach, which is reported in [59], involves (real-time) post-processing of data collected using the system described in [49]. The response of the buried object to the signals radiated by this radar (wideband impulses, subsequently low-pass filtered by propagation through the earth) is sampled in the time domain. After minor signal conditioning (range gating, time shifting, etc.) the complex natural resonances of the target are extracted from the time-domain waveform using Prony's method as suggested by Van Blaricum et al. [60]. These complex resonances and the signal amplitudes associated with them are then used in a predictor-corrector target identification algorithm. It was found that when the local electromagnetic properties of the soil were accurately known, essentially "perfect" performance was obtained (i.e., all identifications were performed correctly), but when said properties were not accurately known, the performance of the system degraded on the order of 10%. Improved performance of this system was obtained by better matching the frequency response of the antenna to the spectral regime containing the target resonances [61].

3.2.1.3 An Assessment of Current Technology

At this time a number of GPR systems have been developed and tested. The literature cited in the foregoing discussion gives evidence of a number of these. In this section we summarize the developments to date. The reader is cautioned that many of the systems described here have only been demonstrated in a research environment. Conversely, the performance demonstrated by these systems is dependent on the hardware configurations available at the time, i.e., more capable systems might be produced by a subsequent development project with well-focused objectives.

For the purposes of this discussion it is helpful to group the existing GPRs into two types based on the surface environment in which they operate. In the first type the antenna is reasonably compact and lightweight, and it can be positioned arbitrarily at the discretion of the operator for the purpose of interrogating a chosen subsurface region. Horizontal resolution is obtained by using antennas with narrow beamwidths. Systems of this type can be used over rough or uneven terrain.

The only system of this type for which quantitative performance estimates have been presented was designed by a group at OSU and described in [35]. This unit, a commercial version of which is now available as the "Terrascan" system [62] is capable of detecting buried metallic and non-metallic utility lines at depths of up to 3 meters. The antenna is a crossed dipole of length 0.6 m, and the entire unit is man-portable. Similar systems are available from ERA Technology, Ltd. in the UK [63], but no performance data are available at this time.

A second type of GPR uses measurements of the subsurface response collected across many points on the surface of the earth. The radar platform for these systems is typically a wheeled cart, for which accurate position information is available (e.g., via position sensors on the wheels), although other platforms, including fixed and rotary-wing aircraft, are also used. The ability to collect scattering data at known positions on the surface permits one to use subsurface imaging and other signal processing techniques, which produce more informative outputs. One of the principal motivations for commercial GPR systems is the detection of buried utility lines in urban environments. The typically smooth air-earth interface in urban environments makes it feasible to gather the data required for these more sophisticated processing techniques.

Subsurface imaging systems are presently able to image metal and plastic pipes at considerable depths. The Groundscan system designed by OSU on behalf of the Electric Power Research Institute [64] has imaged utility lines at depths of up to 4.5 meters. Laboratory experiments presented by Osumi and Ueno [58] indicate that iron pipes buried in a lossy volcanic soil could be located to within an accuracy 10 to 20 cm. A SAR system reported in [65] was able to image buried metal and plastic pipes at depths of up to 2.5 meters. That system is capable of acquiring data while being pulled over the target region at the rate of 3.9 m/s (14 km/hr). Aperture synthesis and image generation require approximately one minute.

The ability of GPR systems to identify buried objects has not been commercialized at this time, and the targets considered in the extant research studies are limited to nonmetallic mines. The performance of systems of this type has been reviewed in the signal processing discussion above. Other systems of this kind have been investigated by Echard et al. [66] who reports comparable results.

3.2.2 Magnetometry

Magnetometry, the measurement of magnetic fields, is used to detect perturbations in the earth's magnetic field caused by the presence of objects made of magnetizable material, especially ferrous objects. An object whose magnetic permeability differs from that of the surrounding medium and which is placed in a static magnetic field will perturb that field in its vicinity. If the perturbation is sufficiently strong, and if a measuring instrument can detect the perturbation, the object can be remotely detected. This principle is the basis for magnetometric detection and location of buried ferrous objects. In this section we review the basic magnetic-field physics involved, we discuss the instruments which are available for the measurement of magnetic fields, and we describe the use of these instruments for the detection and location of buried ordnance.

3.2.2.1 Fundamental Physics

We consider an object made of a material whose relative magnetic permeability μ_r differs from unity (the relative permeability of free space) and which is placed, in free space, in a uniform magnetostatic field $\vec{B}_0$. The total magnetic field is then the sum of the uniform field and the "induced" field caused by the magnetization of the object itself. At distances from the object (which is here assumed to be compact) of a few object lengths or more, the induced field is accurately approximated by its dipole component alone. The induced dipole field $\vec{B}_{i,d}$ is given by

$$\vec{B}_{i,d} = \frac{\mu_0}{4\pi r^3}\vec{m} \cdot (3\vec{a}_r\vec{a}_r - \mathrm{I}) \tag{3.57}$$

where μ_0 denotes the permeability of free space, r is the distance from the center of the object to the observer, $\vec{a}_r$ is the unit vector in that direction, and I is the identity dyadic. The induced magnetic dipole moment $\vec{m}$ is related to the uniform field $\vec{B}_0$ through the object's magnetic polarizability dyadic M as

$$\mu_0\vec{m} = \mathrm{M} \cdot \vec{B}_0 \tag{3.58}$$

The total magnetic field $\vec{B}_t$ is thus expressed as

$$\vec{B}_t = [\mathbf{I} + \frac{1}{4\pi r^3}(3\vec{a}_r\vec{a}_r - \mathbf{I}) \cdot \mathbf{M}] \cdot \vec{B}_0 \tag{3.59}$$

In the simple case where the object is spherical (of radius a), the magnetic polarizability is simply $\mathbf{M} = M\mathbf{I}$ where $M = 3(\mu_r - 1)/(\mu_r + 2)V$ and $V = 4\pi a^3/3$ is the volume of the sphere. In this case, we have

$$\vec{B}_t = B_0\vec{a}_0 + \frac{MB_0}{4\pi r^3}[3(\vec{a}_r \cdot \vec{a}_0)\vec{a}_r - \vec{a}_0] \tag{3.60}$$

where B_0 is the magnitude of the uniform field and $\vec{a}_0$ is the unit vector in the direction of this field. We remark that if the relative permeability is large compared to unity, as will be the case for a ferrous object, the (scalar) magnetic polarizability of the sphere is approximately independent of its permeability and equal to three times its volume.

It will be useful in the following to employ an approximate expression for the magnitude of the total magnetic field, B_t. We assume that the induced field is small in comparison to the "background" uniform field, an assumption almost always true in practice. From eq. (3.59) we find

$$B_t \approx B_0[1 + \frac{1}{4\pi r^3}\vec{a}_0 \cdot (3\vec{a}_r\vec{a}_r - \mathbf{I}) \cdot \mathbf{M} \cdot \vec{a}_0] \tag{3.61}$$

In the special case where the object is a ferrous sphere, we obtain

$$B_t \approx B_0(1 + \frac{M}{4\pi r^3}[3(\vec{a}_r \cdot \vec{a}_0)^2 - 1]) \tag{3.62}$$

3.2.2.2 The Earth's Magnetic Field

In magnetometric detection of buried objects, the uniform magnetostatic field $\vec{B}_0$ is simply the magnetic field of the Earth. The geomagnetic field is not at all uniform on a global scale, but is effectively so over distances of interest in subsurface ordnance detection. The analysis given above for the total field in the vicinity of a magnetizable object can be applied to the ordnance-detection problem in a given part of the world by using the proper "local" values for the magnitude and direction of the geomagnetic field.

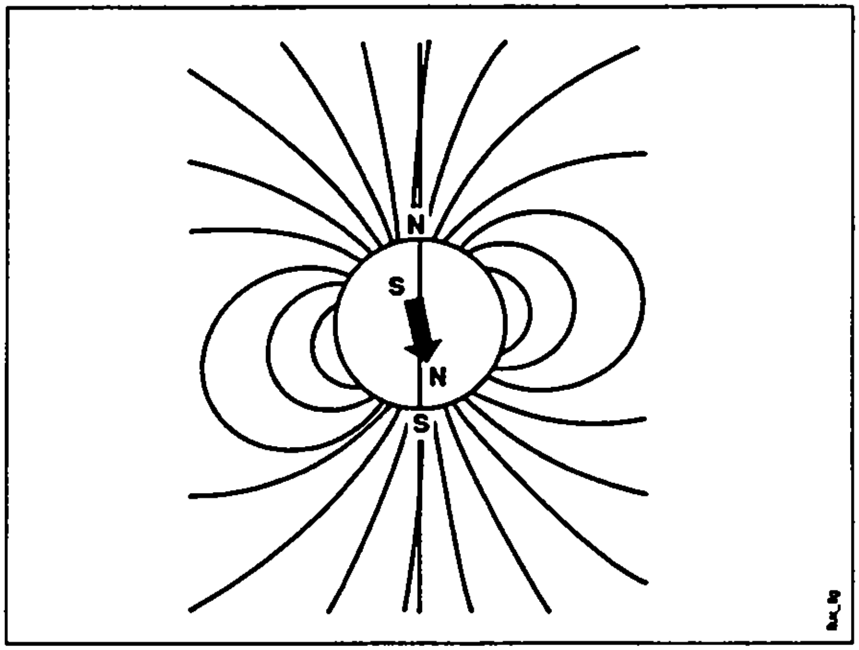

Figure 3.7: The Earth's magnetic field.

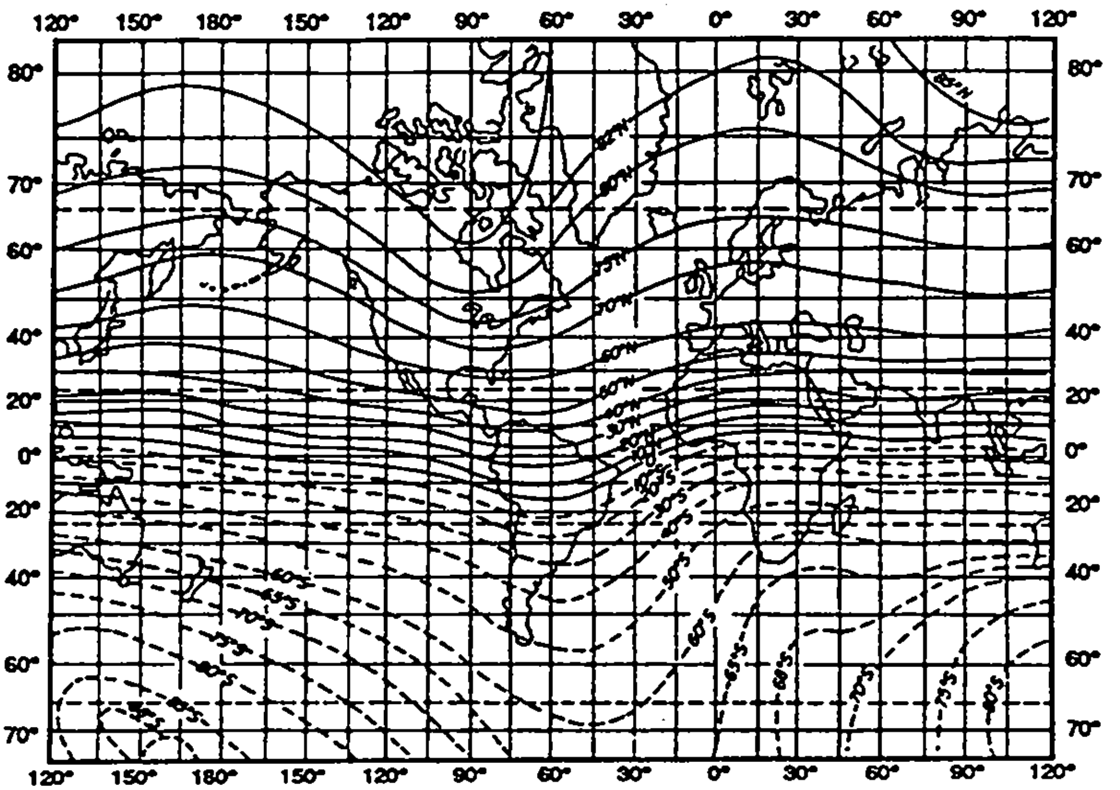

Figure 3.8: Declination angle of the geomagnetic field.

The geomagnetic field is shown schematically on a global scale in Figure 3.7. This field is approximately that of a magnetic dipole whose direction is close to, but does not coincide with, that of the line through the north and south geographic poles. The geomagnetic field lines are approximately normal to the surface of the earth near the magnetic poles and are approximately parallel to the surface near the magnetic equator. The geomagnetic declination, that is, the angle of the magnetic field lines with respect to the horizontal,[5] is shown in Figure 3.8. The declination in the vicinity of the Hawaiian Islands is approxi-

[5]The declination is positive downward in the northern (magnetic) hemisphere.

mately 40 degrees. The horizontal component of the geomagnetic field points approximately 10 degrees east of true north in this area.

The magnitude of the geomagnetic field also varies with position on the earth's surface. The geomagnetic field intensity is shown in Figure 3.9. The intensity in Hawai'i is approximately 37 kilogammas[6]. Thus the geomagnetic field near Kaho'olawe can be represented as a nearly uniform field of magnitude 37 kilogammas whose horizontal component has magnitude 28 kilogammas and whose vertical component has magnitude 24 kilogammas. The horizontal component points in a direction 10 degrees east of true north. The vertical component points downward.

3.2.2.3 Magnetometers and Gradiometers

Several quantities related to the magnetic field near an object are of interest for its detection. The first (but not necessarily the most important) is the magnetic field itself. Since the magnetic field is a vector field in 3-space, each of its three components must be separately measured to determine it completely. The magnitude of the field, B_t, is determined by a single measurement. It is this quantity which is measured by a magnetometer.

The gradient of the field magnitude, ∇B_t, is a vector field describing the spatial rate of change of the field magnitude. This quantity (usually only its vertical component) is measured by a gradiometer. The nine-component dyadic gradient of the magnetic field, $\nabla \vec{B}_t$, describes the spatial rates of change of each of the three components of the total field.

The most common type of magnetometer in use today for detection and location of buried ordnance is the proton-precession instrument. These instruments can measure the magnitude of the magnetic field to accuracies of 0.1 γ. Cesium-vapor magnetometers are also becoming available. Their sensitivity and accuracy are comparable to those of proton-precession magnetometers, but they are capable of making field measurements almost continuously. Their cost is significantly greater than that of proton-precession instruments.

To assess the sensitivity needed in a magnetometer to be used for UXO

[6]The non-SI unit "gamma" (γ) is equal to one nanotesla. One kilogamma is thus equal to one microtesla.

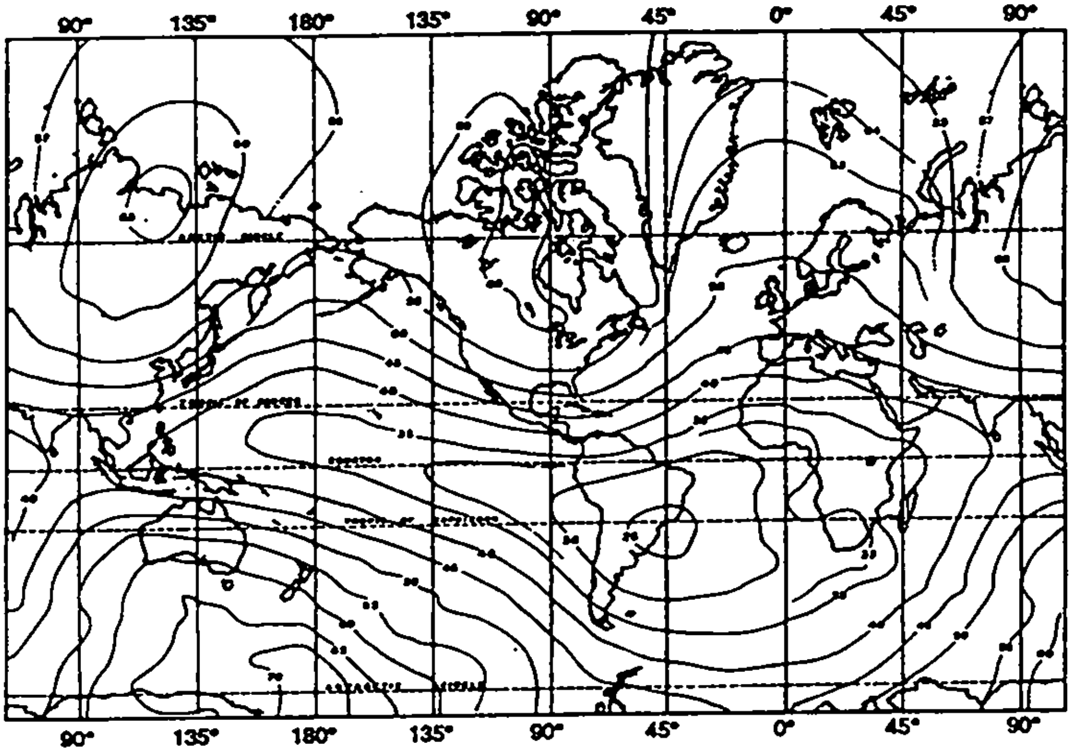

Figure 3.9: Intensity of the geomagnetic field (kilogammas).

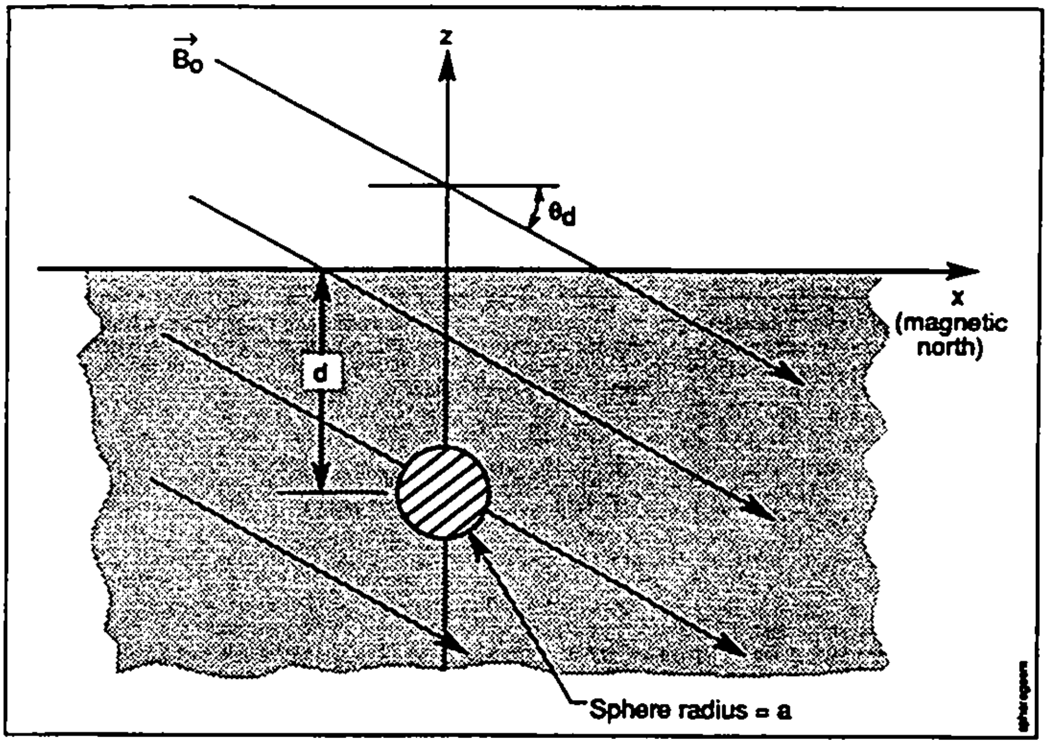

Figure 3.10: Geometry for calculation of the magnetic signature of a buried sphere. The geomagnetic field is parallel to the $x-z$ plane. The positive x-axis is in the direction of magnetic north; the y-axis (magnetic west) points into the page.

detection, let us evaluate the total magnetic field over a ferrous sphere of radius a buried in a nonmagnetic soil ($\mu_r = 1$) at depth d. Let the geomagnetic field be that found in the Hawaiian Islands. We assume that the permeability of the ferrous sphere is effectively infinite. The geometry is shown in Figure 3.10. The (x, y) plane coincides with the earth's surface with the positive x-axis in the direction of magnetic north and the positive y-axis in the direction of magnetic west. The positive z-direction is upward. The object is located at $(x, y, z) = (0, 0, -d)$. Using eq. (3.60) above, we find that the magnitude of the total magnetic field on the surface ($z = 0$) is given by

$$B_t(x, y, 0) = B_0(1 + \frac{a^3}{(x^2 + y^2 + d^2)^{3/2}}[3\frac{(x\cos\theta_d - d\sin\theta_d)^2}{x^2 + y^2 + d^2} - 1]) \qquad (3.63)$$

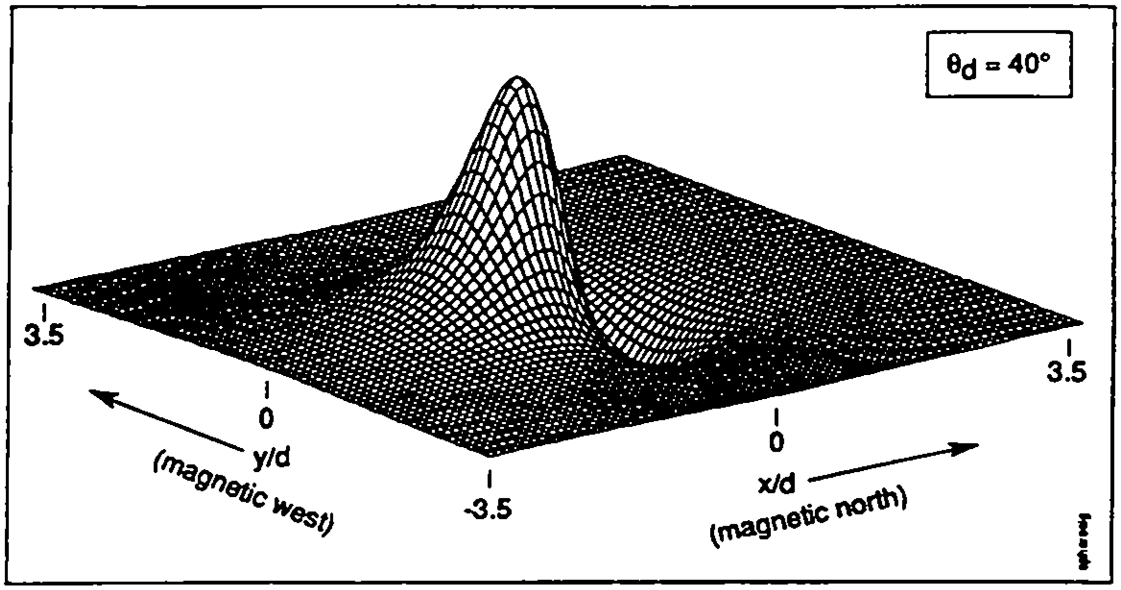

Figure 3.11: Normalized magnetic signature of a ferrous sphere buried at $(0, 0, -d)$ vs. normalized position on the surface.

where θ_d denotes the geomagnetic declination angle. A plot of the normalized function $(d/a)^3[B_t(x, y, 0)/B_0 - 1]$ vs. normalized position coordinates x/d and y/d is shown in Figure 3.11 for $\theta_d = 40°$.

The maximum value of the magnitude of the total magnetic field occurs along the x-axis (that is, along a magnetic north-south path which passes directly over the object) at a position approximately one-half the object's depth to the magnetic south of the buried object. The normalized magnetic signature along such a path is shown in Figure 3.12. The absolute maximum value of this function is approximately 1.1.

We can define an equivalent spherical radius a_e for a given object in terms of its volume V as

$$a_e = (\frac{3V}{4\pi})^{1/3} \tag{3.64}$$

"Standard" objects and depths for ordnance detection are a 155-mm artillery shell at a depth of 1.5 meters, a 250-pound bomb at three meters, and a 500-pound bomb at 4.5 meters. Each of these object size/depth combinations yields a radius-to-depth ratio of approximately 0.1. Multiplying the maximum value

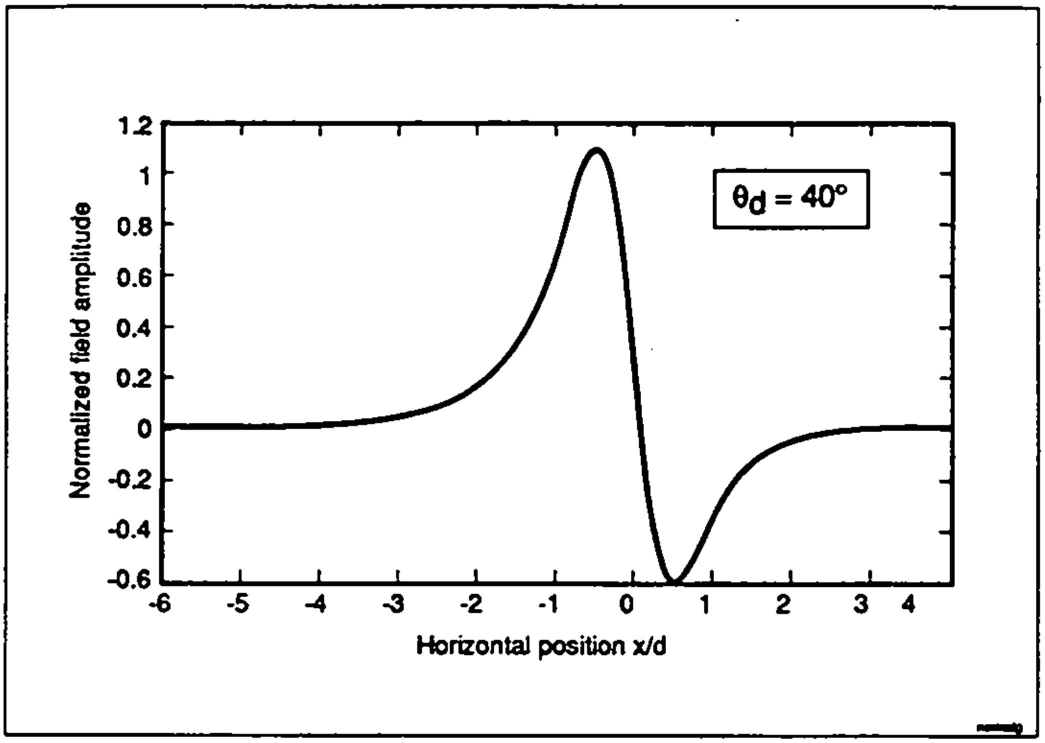

Figure 3.12: Normalized magnetic signature of a ferrous sphere buried at $(0, 0, -d)$ vs. normalized position x/d for $y = 0$.

of the normalized function plotted in Figure 3.12 first by 0.001 (the cube of the radius-to-depth ratio) and then by 37 kilogammas, we obtain a peak amplitude over the background of approximately 41 gammas. In order to reliably detect this signal level, a magnetometer should be accurate to perhaps one-tenth of the peak amplitude or less. This required degree of accuracy is substantially less than that which is commercially available, indicating that available instruments are more than sufficiently accurate for detection of buried ordnance, at least under ideal conditions. We shall have more to say on this matter in the next section.

Let us return to further consideration of eq. (3.63). Normalizing the coordinates x and y and the radius a by the depth d, we find that the magnitude of the total magnetic field takes the form

$$B_t(x, y, 0) = B_0(1 + \frac{\hat{a}^3}{(1 + \hat{x}^2 + \hat{y}^2)^{3/2}}[3\frac{(\hat{x}\cos\theta_d - \sin\theta_d)^2}{1 + \hat{x}^2 + \hat{y}^2} - 1]) \qquad (3.65)$$

where $\hat{x}$ and $\hat{y}$ are the normalized position coordinates x/d and y/d respectively and the normalized radius $\hat{a}$ is equal to a/d. Evidently, the *amplitude* of the perturbation in the total magnetic field depends on the radius-to-depth ratio, while the *spatial scale* of this perturbation depends only upon the burial depth. It is clear from Figure 3.12, for example, that the complete signature of an object buried at a depth of, say, one meter extends over a distance of several meters on the earth's surface. As a consequence, therefore, *one may infer the depth of burial from the spatial scale of the magnetometric signature and the object's size from the peak amplitude of this signature.*

3.2.2.4 Magnetometric Detection of Buried Ordnance

It is evident from the foregoing discussion that existing magnetometers are sufficiently accurate to detect the "standard" objects at "standard" depths. Thus, in principle, the detection and location of subsurface ordnance would appear straightforward. In practice, however, complications arise from a multiplicity of sources. The more important of these for subsurface ordnance detection are listed below:

- surface and shallow subsurface shrapnel and/or other ferrous debris

- remanent magnetization in surface or subsurface rocks
- bulk magnetization of the soil

Ferrous debris (primarily shrapnel) will be present on any former range or target area. The signatures of ferrous debris on or near the surface add to the signatures of the buried objects of interest, making the observed signature appear noisy. It will be recalled that the amplitude of the magnetometer signal decreases as the cube of the depth of the target and increases as the cube of the (effective) radius. The amplitude of the signature of a small object near the surface may therefore be comparable to that of a larger and more deeply buried object.

The proper term for the obscuration of the desired signature by the presence of ferrous debris is not *noise* (which describes random signal variations arising from sources within the instrument), but *clutter*. The problem in magnetometric detection of subsurface ordnance can be posed as a problem of *detection of signals in clutter*. This problem can be attacked in several ways. The most useful is to physically remove surface debris by hand (or by machine, if permitted by environmental constraints) as part of a surface-clearance operation before subsurface investigations commence. One then has a "clean" surface environment in which to work. Removal of small objects on the surface is an extremely important precursor activity in subsurface search for buried UXO items.

In addition to the physical removal of the surface clutter sources, the application of spatial filtering and other signal processing algorithms to field-collected magnetometric data can reduce the clutter signals by mathematical means. Advanced mathematical methods for addressing the clutter problem are under active study by the authors.

Remanent magnetization in subsurface rocks and bulk magnetization of the soil constitute additional sources of clutter signals in magnetometric searches. Remanent magnetization in rocks is often in a direction different from that of the induced magnetization, yielding a signature which may be distinguished from that of objects such as UXO items whose principal magnetization is induced by the geomagnetic field.

Bulk magnetization of the soil can yield a strong contribution to the total magnetometric signature, obscuring the signature of the buried object of interest. The effects of bulk magnetization can be mitigated to a degree by proper data processing of the signature to take advantage of the known shape of the desired signatures. From a practical viewpoint, however, strong bulk magnetization can make magnetometric detection of buried UXO items very difficult. In such situations, electromagnetic induction techniques may be more suitable. These techniques are discussed in the following.

3.2.3 Electromagnetic Induction

The interaction of an electromagnetic field with a conducting body causes electric currents to be induced in the body. When the frequency of excitation is sufficiently low, the induced currents can penetrate deeply into imperfect conductors. These "eddy" currents in turn produce a secondary field which modifies the original (primary) field, and the presence of the secondary field (and, hence, the existence of the conducting body) can be detected by suitable instruments. The creation and detection of such currents is the principle of operation for many of the metal detectors used by treasure hunters and in airport security. Related techniques are also used in geophysical exploration and in nondestructive testing of metal objects.

In this section we discuss electromagnetic induction methods for the detection of subsurface UXO. In subsection 3.2.3.1 we present a brief summary of the physics relevant to electromagnetic induction. In subsection 3.2.3.2 we describe the operation of a possible sensor system, and in subsection 3.2.3.3 we comment on the applicability of such a system to UXO detection.

3.2.3.1 Theoretical Background

The theoretical basis for the calculation of currents induced by low-frequency magnetic fields (i.e., magnetoquasistatic fields) is well known and can be developed as follows: We begin with a subset of Maxwell's equations, viz:

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \tag{3.66}$$

$$\nabla \times \vec{H} = \frac{\partial \vec{D}}{\partial t} + \vec{J} \tag{3.67}$$

$$\nabla \cdot \vec{B} = 0 \tag{3.68}$$

where $\vec{E}$ and $\vec{H}$ are the electric and magnetic fields, $\vec{D}$ and $\vec{B}$ are the electric and magnetic flux densities (or, more precisely, the electric displacement and the magnetic induction), and $\vec{J}$ is the electric current density. The fields and flux densities satisfy the following constitutive relations:

$$\vec{D} = \epsilon\vec{E} \tag{3.69}$$

$$\vec{B} = \mu\vec{B} \tag{3.70}$$

where ϵ and μ are respectively the permittivity and permeability of the medium. When the time scale of interest is much larger than the time required to propagate a signal over a characteristic distance, then one can neglect the displacement current term in equation (3.67), and we obtain Ampère's Law, viz:

$$\nabla \times \vec{H} = \vec{J} \tag{3.71}$$

It is also useful to relate the current $\vec{J}$ to the electric field $\vec{E}$ via Ohm's law as follows:

$$\vec{J} = \sigma\vec{E} \tag{3.72}$$

where σ is the conductivity of the medium. Using equations (3.66), (3.68), (3.71), and (3.72) we obtain the relation

$$\frac{\partial\vec{H}}{\partial t} = \frac{1}{\sigma\mu}\nabla^2\vec{H} \tag{3.73}$$

It will be convenient to express the magnetic field in terms of a vector potential $\vec{A}$ as follows:

$$\vec{H} = \frac{1}{\mu}\nabla \times \vec{A} \tag{3.74}$$

We can readily obtain the relations

$$\vec{E} = -\frac{\partial\vec{A}}{\partial t} \tag{3.75}$$

$$\frac{\partial\vec{A}}{\partial t} = \frac{1}{\sigma\mu}\nabla^2\vec{A} \tag{3.76}$$

Both equations (3.73) and (3.76) are diffusion equations. Similar equations govern the evolution of temperature in solids. One can show from these relations that propagation phenomena are not important in electromagnetic (EM) induction problems: the temporal behavior of the field evolves in time with a smooth (often exponential) behavior.

As we noted in the discussion of ground-penetrating radar, the presence of the earth substantially modifies the fields created by sources near the earth. In EM induction sensors, however, the currents produced in the earth and in the target by these fields are often of greater importance than the fields themselves. Because current flow is proportional to the conductivity of the medium and because the conductivity of a typical metal UXO body is so much larger than that of the surrounding earth, the presence of the earth can be neglected as a first approximation in EM induction analyses. (This situation contrasts sharply with that encountered in geophysical exploration, where relatively minor changes in conductivity must be detected.)

Loops are frequently used both to generate the primary fields in induction sensors and to sense the secondary fields produced by the resulting eddy currents. The quasistatic magnetic field produced by a small transmitting loop of n_T turns with a z-directed axis is well known. We denote the magnetic field produced by this loop as $\vec{H}_p$, and we write

$$\vec{H}_p = \frac{In_T dA_T}{4\pi r^3}\left[\vec{a}_r 2\cos\theta + \vec{a}_\theta \sin\theta\right] e^{-ikr} \tag{3.77}$$

where I and dA_T are the driving current and area of the loop, and (r, θ) are the usual spherical coordinates. The time dependence $e^{+i\omega t}$ is assumed in this result and in the sequel. In some analyses it is convenient to express this field in terms of the dipole moment of the loop, viz:

$$\vec{m}_{loop} = In_T dA_T \hat{n}_t \tag{3.78}$$

where $\hat{n}_t$ is a unit vector which defines the loop axis. The field produced by this dipole is

$$\vec{H}_p = \frac{1}{4\pi r^3}\left[3\vec{a}_r(\vec{a}_r \cdot \vec{m}) - \vec{m}\right] e^{-ikr} \tag{3.79}$$

The voltage induced in a loop by a magnetoquasistatic field can be evaluated in a straightforward manner. Using the integral form of Faraday's law (3.66) in the frequency domain and Stokes' theorem we find that the induced voltage

V_{ind} is given by

$$\begin{aligned} V_{ind} &= -\oint_C \vec{E} \cdot d\vec{s} \\ &= i\omega\mu \int_S \vec{H}_s \cdot d\vec{a} \end{aligned} \quad (3.80)$$

where C is the circumference of the loop, S is the area enclosed by C, and $\vec{H}_s$ is the secondary field received by the loop.

For the electrically small receiving loop we can approximate the final integral by the product of the loop area and the received field. We have

$$V_{ind} = \mu n_R d A_R \hat{n}_r \cdot \vec{H}_s \quad (3.81)$$

where $\hat{n}_r$ is a unit vector which defines the receiving loop axis.

Several further simplifications of this result are useful. In the quasistatic frequency regime, the loops and the potential targets are electrically small and it is reasonable to express the fields generated by them in terms of equivalent dipole moments. We can express the magnetic dipole moment $\vec{m}$ of an object in terms of its magnetic polarizability $\mathbf{M}$ as follows:

$$\vec{m} = \mathbf{M} \cdot \vec{H}_p \quad (3.82)$$

where $\vec{H}_p$ is the magnetic field that would exist in the absence of the object. The induced voltage in equation (3.81) involves the unknown field $\vec{H}_s$. By using the reciprocity theorem [67], we can eliminate this dependence in favor of the field transmitted to the object. We can show

$$V_{ind} = \frac{i\omega\mu}{I} \vec{m} \cdot \vec{H}'_p \quad (3.83)$$

where $\vec{H}'_p$ is the field that would be produced at the target when the receiving loop is driven by a current I. We note that because the location of the object and its dipole moments are unknown, the quantity $\vec{m} \cdot \vec{H}'_p$ is, like $\vec{H}_s$, unknown, but the form in equation (3.83) is somewhat more convenient for the calculations that will follow.

One can create a sensor of induced magnetoquasistatic fields which operates with either CW or pulsed fields. For CW operation the frequencies of interest are a few Hertz to a few kilohertz. The target couples inductively to the receiving antenna, and the receiver detects the change in the effective induction of the circuit. In practice, this detection may be done by either cancelling the transmitted field, or by detecting a change in the frequency of a resonant circuit.

For a pulsed system, the transmitter generates a transient magnetic field of short duration. After this primary field has decayed, the receiver attempts to detect the secondary field which arises from the eddy currents. One can show that these currents decay approximately exponentially with time and, hence, the interval between pulses must be determined with the response time of the target in mind. Further discussion of these topics is presented in the sequel.

3.2.3.2 Description of a Typical Instrument and Expected Signatures

We have noted previously that inexpensive sensors based on EM induction are widely used to detect buried metallic objects. These "metal detectors" comprise a single small loop which is used for transmission and reception. The loop, which located at the end of a hand-held probe, is moved over the surface of the earth. A CW magnetic field produced by the loop excites currents in buried objects which affect the self inductance of the loop. This change in inductance can then be detected as a change in the resonance frequency of a tuned circuit. Although the sensitivity of these inexpensive commercial probes is somewhat limited, the general theory of operation can be extended to systems with more acceptable level of performance.

In this section we review the essential features of a simple induction-based UXO detection system. The postulated system consists of a pair of coaxial, coplanar loops oriented parallel to the interface. For the purposes of this analysis we assume that the same loop is used for transmission and reception so that $\vec{H}_p = \vec{H}'_p$. From equations (3.82) and (3.83) we find

$$V_{ind} = \frac{i\omega\mu}{I}\left[\mathrm{M} \cdot \vec{H}_p\right] \cdot \vec{H}_p \qquad (3.84)$$

To investigate the performance of such a system, we will consider detection of a spherical target of radius a. The eddy currents induced in this body have been calculated previously [68, 69], and we find

$$\mathbf{M} = 2\pi D \mathbf{I} \tag{3.85}$$

where $\mathbf{I}$ is the identity dyadic and

$$D = \frac{(2\mu_r + 1)uI_{-1/2}(u) - (1 + 2\mu_r + iu^2)I_{1/2}(u)}{(\mu_r - 1)uI_{-1/2}(u) + (1 - \mu_r + iu^2)I_{1/2}(u)} \tag{3.86}$$

In this expression $\mu_r = \mu/\mu_0$ is the relative permeability of the sphere, $I_{1/2}$ and $I_{-1/2}$ are modified cylindrical Bessel functions of the first kind and orders $\pm 1/2$, and

$$u \equiv \sqrt{i\omega\mu\sigma}a = (1 + i)\frac{a}{\delta} \tag{3.87}$$

in which σ is the conductivity of the sphere and

$$\delta \equiv \sqrt{\frac{2}{\omega\mu\sigma}} \tag{3.88}$$

is the skin depth of the target.

The expression for D simplifies considerably in some important cases. For a highly magnetic body we have $\mu_r \gg 1$ and

$$D \approx 2a^3\frac{\mu_r - 1}{\mu_r + 2} \tag{3.89}$$

which indicates that the static-like magnetic currents dominate the conduction currents. If the skin depth δ is much larger than the radius a (i.e., if the fields penetrate well into the target), then small-argument evaluation of the Bessel functions produces

$$D = 2a^3\frac{\mu_r - 1}{\mu_r + 2}\left[1 - i\frac{a^2}{5\delta^2}\frac{3\mu_r}{(\mu_r - 1)(\mu_r + 2)} + \cdots\right] \tag{3.90}$$

If the skin depth is small and the sphere is also nonmagnetic ($\mu_r = 1$), then we obtain

$$D = -ia^3\frac{2a^2}{15\delta^2} \tag{3.91}$$

In this case the induced current is due entirely to the conduction currents flowing in the body. When the skin depth is small compared to the radius, we find

$$D \approx a^3 \frac{2\mu_r - u}{\mu_r + u} \tag{3.92}$$

The induced current flows primarily within a surface layer of depth δ, and the amplitude of the current attenuates exponentially in depth. When we have, in addition, $a/\delta \gg \mu_r$, equation (3.92) simplifies to

$$D = -a^3 \tag{3.93}$$

The dependence of the induced voltage on various parameters can now be studied. From (3.84) and (3.85) we obtain

$$\begin{aligned} V_{ind} &= \frac{2\pi i\omega\mu}{I} D\vec{H}_p \cdot \vec{H}_p \\ &= i\omega\mu I n^2 D(dA)^2 \frac{1 + 3\cos^2\theta}{8\pi r^6} e^{-2ikr} \end{aligned} \tag{3.94}$$

We find that the induced voltage is proportional to the transmitter current I, to the volume of the target (approximately, via D), to the square of the area of the sensor loop dA, and to the inverse sixth power of the target-sensor range r.

At this point it is instructive to compare and contrast the operation of sensors based on electromagnetic induction with ground-penetrating radars and magnetometers. Both EM induction detectors and GPRs are active systems: they generate a field which induces currents in the target. These currents create secondary fields which are subsequently detected. In GPR, the distances and frequencies are so large that the fields are transmitted by wave propagation, while in EM induction the fields have the character of static fields, but with some (slow) time variation. Wave propagation is a considerably more efficient method to transmit energy: a propagated field decays like r^{-1}, while a quasistatic field decays as r^{-3}. For both EM induction and GPR it is necessary to square these signal losses to account for signal transmission to the target and back to the receiver.

In contrast, a magnetometer is a passive device. The fields detected by this sensor are perturbations on the natural ambient field (the geomagnetic field). The received fields are dependent only on the distance between the target and the receiving loop. Finally, we note that the magnetometer fields are purely static in nature. Collectively, these conditions reveal that the signal produced by a magnetometer varies as r^{-3}.

As noted above, pulsed EM induction systems are also of interest, but the required analysis is too involved for this overview presentation. Nonetheless, some insight can be obtained from a study of the final result. Smythe [69] has shown that the unit step response of a conducting sphere to a uniform z-directed magnetic field is given by

$$\vec{H}_s = \frac{a^3}{r^3}\left(\vec{a}_r 2\cos\theta + \vec{a}_\theta \sin\theta\right)\left[\frac{\mu_r - 1}{\mu_r + 2} - \sum_\nu \frac{3\mu_r}{(k_\nu a)^2 + (\mu_r - 1)(\mu_r + 2)} e^{-k_\nu^2 t/\sigma\mu}\right] \tag{3.95}$$

where k_ν is a solution of the equation

$$(k_\nu a)\frac{d}{d(k_\nu a)} J_{3/2}(k_\nu a) + (\mu_r + 1/2) J_{3/2}(k_\nu a) = 0 \tag{3.96}$$

in which $J_{3/2}$ is the cylindrical Bessel function of the first kind and order 3/2. [Here the subscript ν indexes the roots of equation (3.96).] Equation (3.95) indicates that the transient fields produced by the sphere have the spatial dependence normally associated with dipolar fields. The time dependence of this result enters through a series of exponentials which approaches the well-known static limit as $t \to \infty$. Roots of equation (3.96) must be determined numerically. We find that for $\mu_r = 120$ (typical of iron) the first few roots of this equation are $k_1 a = 4.5$, $k_2 a = 7.7$, and $k_3 a = 10.8$ from which we can calculate effective time constants via $\tau_\nu = \sigma\mu/k_\nu^2$. It is also easily shown that the roots approach $k_n a \sim n\pi$ for large n. The lower-order terms in equation (3.95), which correspond to more slowly decaying exponentials, arise from currents which penetrate the sphere more deeply, while the higher-order terms arise from near-surface currents. In addition, it is evident that, as expected, smaller spheres will have shorter decay times. The response of the sphere to a short rectangular pulse is approximated by the derivative of the fields in equation (3.95). One finds that the lower-order terms in equation (3.95) are less significant in the pulse response and, although the net response decays to zero exponentially, an effective time constant for the system is not evident from this analysis.

Another relevant line of analysis has been presented by Lee [70, 71] who has evaluated the response of a sphere in the presence of an overburden. In his investigation Lee evaluates the contributions of several diffraction phenomena, and he is also able to separate the response of the sphere from that of the earth. Further details are available in the cited works.

3.2.3.3 Detection of Buried Ordnance via EM Induction

It follows from the r^{-6} dependence noted above that detection by EM induction is potentially limited in range. This situation can be compared with the r^{-3} behavior encountered for the passive magnetometric methods, and the r^{-2} decay (with exponential soil losses) found for GPR. In spite of this range dependence, however, it is possible to obtain EM induction target signals which are highly detectable. In this section we present a calculation of the signal-to-noise ratio expected for a simple UXO detection system.

As an example UXO detector, we consider the system proposed by Das et al. [29]. The system under consideration has a loop area of approximately 1 m^2 with n =28 turns per loop. Nearly coincident transmitting and receiving loops were used. The current in question was a rectangular pulse train with a 3 Ampere peak, but in our analysis we will consider a CW source of frequency 60 Hz. We assume that the target is composed of ferrous metal with $\mu_r = 120$ and $\sigma = 10^7$ S/m. At $\omega = 2\pi 60$ rad/s, we find a skin depth of $\delta \approx 1/(2\pi\sqrt{\mu_r}) = 0.19$ cm. It follows that the eddy currents in this case are confined to regions quite near the surface, and the presence of voids in the target is of no consequence.

The magnitude of the voltage induced in the receiving coil can be evaluated for some example targets. We employ the expression for D presented in equation (3.92), to obtain

$$V_{ind}(\omega) = i\omega\mu I n^2 (dA)^2 \frac{1 + 3\cos^2\theta}{8\pi r^3} \frac{a^3}{r^3} \frac{2\mu_r - (1+i)a/\delta}{\mu_r + (1+i)a/\delta} \tag{3.97}$$

Using the "standard" ordnance objects defined in Section 3.2.2 we find that estimates of the effective radii for the targets range from 15 to 50 cm, and burial depths range from 1.5 to 5 meters. For these objects $a/r \approx 0.1$. Considering only the case in which the sensor is directly over the object, we find that the voltages induced in the receiving loop by these objects range from 25 mV for the 0.1 m radius object at 1 m depth to 100 μV for 0.5 m radius object at 5 m depth.

The noise signal presented to the receiver will depend strongly on the design of the system. As an initial estimate of the magnitude of this signal, we will consider only the effects of Johnson-Nyquist (thermal) noise (cf. Section 3.2.1.1). We have

$$\sigma_{nn}^2 = K T_0 F_n B \tag{3.98}$$

where $K = 1.38 \times 10^{-23}$ [J/K] is Boltzmann's constant, T_0 [K] is a reference noise temperature (taken to be 290 K by convention), B is the receiver bandwidth, and F_n is the receiver's noise figure. Other noise sources of importance in a practical sensor will include shot noise arising in the sensor electronics and quantization noise in A/D converters. The effects of these noise sources are, in part, subsumed by the noise figure F_n. As estimates of the capability of existing systems, we take $F_n \approx 10$ and $B = 1$ Hz. We find noise powers of roughly 4×10^{-20} W. Assuming that this power is developed in a 50 Ohm resistor, we find (voltage) signal-to-noise ratios of 10^5 to 10^7, which are more than adequate to insure detection. Acceptable results are also obtained if we decrease the loop size to a more manageable area of 0.1 m^2, and decrease the loop current to some tens of mA.

As in the case of the magnetometric sensor, clutter has an important effect on detectability. Near surface clutter, which includes conductive soils, tree roots, and surface debris (expecially shrapnel), can easily overwhelm the more deeply buried target signature through the r^{-6} range dependence. We also note that EM induction sensors, unlike magnetometers, respond to all electrical conductors (which includes all metals and some biological materials) and not just to ferrous metals.

A technique which can potentially discriminate the desired target signals from clutter involves the use of transient EM induction sensors. Since the shape of an object influences the rate at which the object's eddy currents decay, the decay times measured by the sensor are suggestive of the object's identity. Further, since the currents on smaller objects decay more rapidly than the currents on large bodies, it is possible (in theory) to eliminate the response of small surface clutter on the basis of its decay rate. There is, however, no evidence in the literature that this potential identification technique has been explored. Target identification approaches based on the spatial response of a target [29], and on images of objects [72] have, however, been examined with limited success.

3.3 New Detection and Location Technologies

Of late a surprisingly large number of new technologies have been developed for the detection of explosives and other concealed objects [73, 74]. In most cases, the development of these concepts has not progressed beyond the stage of laboratory research. Nonetheless, some of the results are encouraging, and future work in these areas may lead to systems of use in future UXO clearance operations.

3.3.1 Thermal Neutron Activation

As noted in Section 3.1.3, nuclear detection (i.e., the detection of an induced change in the atomic structure of a substance via, for example, particle emission) is a potential means of locating UXO. At this time, such methods have had some success as airport security monitors and in locating land mines. In this section we review the bases for some of the more successful applications of this technology.

We first note that x-ray detection methods, such as those commonly employed in airport security systems, are not applicable to UXO detection. The basis for these detection methods is the poor transmission of x-rays through metals and, without access to both sides of the interrogated region, it is impossible to estimate transmission rates.

The basis for most existing methods of nuclear detection is "activation" of nitrogen atoms, in which, the nitrogen atom is excited into a high-energy state. As noted previously, nitrogen is relatively rare in the natural environment (including soils), but it is present in large quantities in virtually all explosives.

One of the better known nuclear detection methods employs thermal neutron activation of nitrogen [38]. In this approach, neutrons emitted by radioisotopes such as Californium (^{236}Cf) or by particle accelerators are directed at a suspect object. The neutrons produced by ^{236}Cf exhibit a range of energies from near zero up to 10 million electron volts (MeV). Interaction of the higher-energy "fast" neutrons with matter consists primarily in collisions, in which the neutrons lose energy until, ultimately, the energy of the neutrons is reduced to that of the ambient material (about 0.25 eV at room temperature).

All atoms have some potential to absorb the slower "thermal" neutrons, and some materials can absorb the faster neutrons. The absorption of a neutron places the atom in an activated state and, in most cases, the atom immediately emits energy in a series of gamma rays. The relevant reaction is

$$^{14}\mathrm{N} + \text{thermal neutron} \rightarrow {}^{15}\mathrm{N} + \gamma \tag{3.99}$$

Gamma ray (photon) detectors are able to determine the energy of the incident photons by converting them into visible light and measuring the intensity of this light. A key point in the operation of this sensor is that the gamma rays emitted by nitrogen are of very high energy (approximately 10.8 MeV). This fortuitous situation leads to a readily detected and easily identified signature for most explosives.

Considerable effort has been directed toward the development of an explosive detector based on thermal neutron activation. To date, such detectors have been developed and tested at several airports including Los Angeles and San Francisco International Airports; John F. Kennedy International Airport (JFK), New York; Miami International Airport; Dulles International Airport, near Washington D.C.; and Gatwick Airport, near London. It was found that detection rates near 100% can be achieved, but only with a significant false alarm rates (18% to 20%)[38].

An interesting variation on this detection approach involves the use of fast neutrons to activate oxygen and carbon in addition to nitrogen. Simultaneous detection of nitrogen and oxygen, both of which are present in explosives in large quantities, can help to minimize false alarms at the cost of an increase in sensor complexity. Further investigation of this approach is in progress.

The applicability of thermal neutron activation to range clearance is somewhat limited. Although soil has a very small nitrogen content and therefore provides a small background, thermal neutrons have a limited ability to penetrate to the depths of interest. Moreover, the presence of a metallic shell casing can be effective both in shielding the explosive charge from the neutrons and in preventing the gamma rays from propagating back to the detector. The use of fast neutrons could be advantageous in overcoming this problem.

Following [73], we conclude that the detection of shallow, nonmetallic mines via thermal neutron activation is limited by poor detector sensitivity and the size and bulk of the neutron source. Further developments in these areas may produce more effective systems in the future.

3.3.2 Electron-Beam X-Ray Activation

Another promising nuclear detection method involves the use of a charged particle beam to produce, via interaction (bremsstrahlung) with a titanium or tantalum target, x-rays which activate the nitrogen in the explosive. This concept, which was shown schematically in Figure 3.2, is presently under development by the TITAN Corporation as part of a joint DARPA/Sandia National Laboratory-sponsored countermine research initiative [75].

In this approach, which has become known as MIDEP (Mine Detection with Energetic Photons), the stable isotope ^{14}N in the mines absorbs an incident 13.5 MeV photon and is converted into ^{13}N which decays (with a half-life of some ten minutes) into ^{13}C and a positron. The positron immediately undergoes an annihilation interaction resulting in two 0.511 MeV gamma rays that are easily detected using standard techniques. One finds that elements in the environment other than nitrogen which could produce confounding signals have activation energies somewhat above that of the incident 13.5 MeV x-rays and, hence, a relatively large signal-to-background ratio is possible.

The operation of the MIDEP system involves illuminating the suspected region of soil with the intense x-ray source, and soon thereafter passing over the same area with a gamma ray detector. In experimental tests, it was found that this system was capable of detecting 9.5 kg mines with a 10 cm overburden, 1.5 kg mines with a 5 cm overburden, and 0.2 kg mines on the surface. Detection was found to be robust, even when the soil was rich in organics, which contain nitrogen, and phosphorus. (Phosphorus also undergoes positron emission after x-ray exposure.)

The equipment necessary to operate the MIDEP system is not easily transported. To produce the energetic x-rays, it is necessary to generate an intense electron beam. In the current experimental system this beam is generated by a linear accelerator (linac) which is in turn driven by a 6.5 MW source of pulsed radio frequency (rf) power. One proposed design for a fieldable mine detection system employs a remotely operated five ton truck to transport a 60 kW generator, the linac, and a sensor array. (Remote operation of the vehicle is necessary because it is not feasible to provide adequate radiation shielding for a human operator.) It has been asserted that the proposed system can with high confidence detect buried mines at speeds of three to five miles per hour. A portable version of the system, transported in five two-man parcels, has also been proposed.

The applicability of the MIDEP concept to UXO detection appears limited. The existence of signal attenuation by the overburden and shell casings suggests that it will be difficult to detect UXO at the depths of interest. In addition, it appears that the size and weight of the system make it difficult to transport over uneven, vegetation-covered terrain. Future developments in accelerator technology may mitigate these limitations to a degree.

3.3.3 Two-Color IR Thermal Sensing

As noted in Section 3.1.4, it is possible, in theory, to detect the changes in soil surface temperature that are caused by buried objects. The signals produced by common clutter sources, however, make this detection difficult. Researchers at LLNL have shown that the clutter can be greatly reduced by using two IR sensors at different wavelengths (different "colors"). In this section we briefly describe the theoretical basis for the LLNL device, and we comment on its applicability to the detection of buried UXO.

The radiant emittance (exitance) E [W/m^2] detected by an observer viewing the earth at infrared wavelengths can be written as the sum of emittances which arise from the warm earth and from the radiometric background. We have

$$E(x, y, \lambda) = E_T(x, y, \lambda) + E_B(x, y, \lambda) \tag{3.100}$$

where x and y are horizontal surface coordinates, λ is the source wavelength, E_T is the exitance due to thermal emission by the earth, and E_B is the background exitance. The thermal emittance from the earth is given by

$$E_T = \epsilon(x, y) M(T(x, y), \lambda) \tag{3.101}$$

where ϵ is the emissivity of the earth at position (x, y), $T(x, y)$ is the temperature of the earth at that position, and M is the emittance of a blackbody radiator at wavelength λ and temperature $T(x,y)$.[7] In this work we make the reasonable approximation that the emissivity is wavelength independent.

The background emittance E_B derives from thermal emission of the air column through which the signal passes and from scattering of background IR radiation by the earth's surface. The thermal radiation from the atmosphere is well understood and smoothly varying and, in the sequel, we ignore its effect. We are, therefore, led to express the background exitance as the power density scattered by the surface, viz:

$$E_B = M_0(T_a,\lambda)\rho(x,y) \tag{3.102}$$

where T_a is the temperature of the air, $\rho = 1 - \epsilon$ is the reflectance of the soil, and M_0 is the effective emittance of the background radiation. The latter quantity derives from direct and scattered sunlight and thermal emission by the air column.

Using the foregoing development, we find that if one collects two images of a scene at wavelengths λ_1 and λ_2, the following data result:

$$E(x,y,\lambda_1) = \epsilon(x,y)M(T(x,y),\lambda_1) + [1-\epsilon(x,y)]M_0(T_a,\lambda_1) \tag{3.103}$$
$$E(x,y,\lambda_2) = \epsilon(x,y)M(T(x,y),\lambda_2) + [1-\epsilon(x,y)]M_0(T_a,\lambda_2) \tag{3.104}$$

The phenomena described by $M(T,\lambda)$ and $M_0(T_a,\lambda)$ are well understood and, hence, it follows that at each image position (x,y) there are two unknowns, $\epsilon(x,y)$ and $T(x,y)$. The above two (nonlinear) equations can, through an appropriate procedure, be used to solve for these unknowns and thus the temperature distribution T can be determined.

An implementation of this approach by its originator at LLNL has produced temperature maps with a thermal resolution of 0.2 C [76, 77]. The significance of this resolution is made manifest by noting that single-wavelength IR imaging systems must contend with variations in emissivity which are equivalent to temperature changes of 1 C to 2 C. Hence, the use of two wavelengths for suppressing clutter leads to an improvement in sensitivity of an order of magnitude. In its present form the system has detected inert surrogate land mines buried at depths which ranged from 1" to 4" using various wavelengths [77].

[7] The signal emitted by the earth is scattered, absorbed, and re-emitted during its propagation between the viewed region and the sensor. It is possible to account for these effects in the analysis, but we omit the relevant discussion in the interest of brevity.

Although the sensor described above can produce an accurate estimate of the temperature distribution in a scene, there are many temperature variations in a scene which are independent of subsurface anomalies. These variations constitute an unavoidable source of clutter for this sensor. Several important examples of undesirable temperature variations are (1) thermal absorption and reradiation by vegetation; (2) wind-driven air motion past vegetation, which can produce a thermal "plume"; and (3) sources of shade (vegetation and surface features). To our knowledge, detection of small (land-mine sized) objects using this system has only been attempted on cleared, level surfaces which included parking lots and grassy fields. In the latter environment, gopher holes were observed to be a source of false detections. These findings have obvious implications for UXO detection in rough terrain.

The existence of natural subsurface thermal anomalies gives rise to other confounding influences. For example, rocks often have a thermal conductivity much larger than the overburden, and, hence, the signatures produced by buried rocks are another potential source of clutter. The presence of water in the soil as a result of, for example, irrigation or natural drainage, can also affect the thermal properties of soil.

The foregoing discussion suggests that, at this time, two-color thermal imaging is not an appropriate technology for the detection of buried UXO. The data extant which describe this sensor suggest that its temperature sensitivity, while exceptional for sensors of this type, is nonetheless inadequate to detect any but the most shallow objects in UXO clearance operations. Further, there are numerous harmless sources of temperature variations in the natural environment, including vegetation, subsurface water, and buried rocks, which are an unavoidable source of clutter for the system. We conclude that the two-color imaging system in its present form may be useful for shallow clearance of vegetation-free terrain, but in other applications is unlikely to be successful.

3.3.4 Vapor Detectors

All explosives emit vapors to some degree. With appropriate instruments it is possible to sense these vapors and to separate them into specific molecular and ionic components for identification. Related instruments are presently under investigation for airport security.

Several techniques have been used to analyze trace gases, and at present it appears that the techniques of chemical ionization mass spectrometry (CIMS) and plasma chromatography have the potential to detect near-surface explosives.

Mass spectrometers are widely used in chemical analysis. These devices operate by ionizing a portion of the sample. The ions thus produced are then accelerated in electric and magnetic fields and subsequently deflected by a uniform magnetic field. Since the degree of deflection is related to the mass of the particle, mass spectrometers produce a signature which indicates the masses of various molecular and ionic constituents of the sample. The signatures produced in this manner tend to be highly informative. Often, the peak of the signature (the mass spectra) will correspond to a minimally ionized form of the sample, from which information the mass of the sample can be inferred. The manner in which ionization is performed has a bearing on the success of these techniques in UXO detection. Conventional mass spectrometers use electron impact ionization which, by virtue of the large energies involved, tends to produce more complete fragmentation of the sample and, hence, more complex signatures. The efficiency of this ionization method also tends to be low, leading to poor sensitivity. Chemical ionization mass spectrometers employ low energy reactions between the sample and a neutral trace gas (typically methane or nitrogen-ammonia at a pressure of one Torr). The spectra of these devices tend to be somewhat less complex. Further, by operating these devices with air at atmospheric pressure, the rate of reaction is increased with a resulting increase in sensitivity.

Plasma chromatography utilizes reactions between the sample and ions of a reagent gas. Such reactions are designed to produce ionized compounds involving the sample. These ions are injected into a drift tube where they move under the influence of an applied electric field. The drifting compound is sampled at points along the length of this tube to obtain an estimate of the mobility of the various ionic constituents (an ion mobility spectrum). The resulting signatures can be quite similar to those obtained via the CIMS technique described above, and their use in sample identification follows similar lines.

It is also interesting to note that biological methods can be used to identify trace gases. Perhaps the best known vapor detector is the dog. The mammalian olfaction system is among the most sensitive detectors known and, although dogs have been used extensively as explosives detectors when specific areas must be searched, it is not feasible to use these animals when large regions must be searched [74]. It has also been noted that certain bacteria bioluminesce in the presence of specific explosive vapors, but these organisms are not presently sensitive enough for UXO detection work and they cannot discriminate against common background gases. A related technique is fluoroimmunoassay, wherein organisms designed through bioengineering produce antibodies upon exposure to various explosives. The antibody, which is tagged with a fluorescently labeled radical, reacts to the presence of the explosive by freeing the radical which is detected by its fluorescence.

A number of problems are encountered in attempting to detect vapors from UXO [73], the most serious of which is the fact that the explosive charge in an artillery round is hermetically sealed. Although the integrity of such seals may degrade with time, an additional problem is that diffusion of any explosive vapors through the soil overburden leads to tremendous signal attenuation. Further, the presence of explosive residues on the surface creates a signal which can mask the vapors emitted by any subsurface UXO. At present, it appears that detection of vapors from near-surface mines may be possible, but vapor-based detection of artillery rounds appears unlikely.

Although some of the techniques described show promise as detectors of explosives, we conclude that none are presently useful in UXO clearance operations involving artillery shells. Further, it has been estimated that the most sensitive method, CIMS, will required improvements in sensitivity of one to two orders of magnitude before it can be considered for use in detecting near-surface mines [73]. Finally, we note that these techniques are not directional. The presence of wind or subsurface obstructions could easily misdirect clearance efforts.

3.4 Detection and Location on Kaho'olawe

We have reviewed detection and location technologies in the earlier sections of this chapter. We now consider the applicability of the electromagnetic techniques, which we believe will prove to be the most useful of all the techniques considered in the foregoing, to the problem of UXO detection and location in general, and on Kaho'olawe in particular.

3.4.1 Ground-Penetrating Radar

In assessing the applicability of GPR to UXO clearance we first note that the amount of system performance data which is directly relevant to the UXO problem is small. We noted previously that detection of buried utility lines is the primary application of commercial GPR systems and, as a result, performance is often quoted in terms of the depth at which pipes or cables can be detected. It is difficult to infer UXO detection capability on the basis of pipe detection depths, since the effective "cross section" of an extended body such as a pipe may be large compared to that of an UXO item. There is no evidence that the ability to detect UXO has been carefully assessed for any of the systems discussed here. The ability to detect land mines is also not directly relevant, since these targets are generally nonmetallic and typically have burial depths of no more than 0.3 meters.

Despite a lack of quantitative performance data, it is possible to make several significant observations about the role of GPR in UXO clearance operations. In principle, GPR can detect not just metallic objects, but dielectric bodies and voids as well. This fact makes GPR theoretically more flexible than magnetometers and electromagnetic induction devices. This flexibility may be advantageous for some applications. GPR range profiles also give an immediate estimate of the depth and size of the target—quantities which are not immediately available from other sensors.

Some of the limitations of GPR systems are evident from the foregoing discussion. These are as follows:

- The majority of GPR systems are not portable: they require either a wheeled cart or a support vehicle. The few systems which are man-portable have limited range and poor horizontal resolution.
- The detection range of a GPR system can be quite limited, particularly in soils which are highly lossy. The detection problem can be overcome to a degree by using higher transmitter power, but higher power frequently implies larger, heavier systems.
- Many GPR systems are adversely affected by surface irregularities including rough terrain and vegetation. Since UXO is typically found in

unpopulated areas, this limits the usefulness of GPR systems for UXO detection.

- Surface clutter and buried inhomogeneities can lead to undesired detections. The ability of a GPR to discriminate undesired objects from the targets of interest has only been demonstrated in a research environment, and then only with shallow nonmetallic mines.

- GPR data which have not been subjected to extensive processing are frequently hard to interpret. More meaningful results can be obtained by detailed sampling of the surface fields, but it is not possible to acquire the data required for such processing in the presence of rough terrain or vegetation.

- Assessing the potential range of the radar or the depth of a detected object requires *a priori* knowledge of the local soil properties.[8] Field measurements of these quantities is sometimes possible, but it is seldom convenient.

It should be noted that many of these limitations are not intrinsic to the physics of GPR. For example, the ability of a system to deal with surface clutter and vegetation could, in principle, be improved via suitable signal processing. Similarly, the development of new light-weight, high-power, broadband microwave sources may lead to GPRs with greater detection ranges. At this time, however, the technology necessary to construct a GPR system which is well suited to UXO clearance has not been demonstrated.

We conclude that while GPR systems are one of the few available potential methods of detecting buried nonmetallic objects, their use is essentially limited to relatively shallow targets. The performance of these radars is enhanced in regions with relatively smooth surfaces and, therefore, it may be appropriate to use them in broad-area sweeps of lands which are being prepared for development, or in surveys of other level, vegetation-free areas. The use of GPR in combination with other sensors in such areas is particularly attractive. Broad

[8]Soil samples have been gathered from six locations on Kaho'olawe and shipped to the Laboratory for Advanced Subsurface Imaging at the University of Arizona for analysis. The results of this analysis, which has not been completed as of the time of writing, will enable an assessment of the useful depths of penetration of GPR systems on Kaho'olawe.

area scans (via aircraft) for large buried objects (e.g., buried drums of waste, buried weapons, cables) are also a potential application of these sensors.

The potential for future developments in GPR systems with relevance to UXO clearance is excellent. A number of groups (primarily in the US, Japan, and the UK) are doing GPR research for various purposes. It is reasonable to expect future GPR systems to be more portable, more sensitive, and to employ more sophisticated signal processing. The latter development is expected to ease the problem of interpreting the output of these sensors. Techniques for convenient *in situ* measurement of the electromagnetic properties of soil must also be developed. There is evidence of preliminary work along this line in the literature. Finally, although encouraging target identification results have been presented, this important topic appears to be in its infancy. It is unlikely that GPR systems with robust false-target rejection will be fielded in the near future.

3.4.2 Magnetometry

Magnetometry is the method of choice within the US EOD community for detection and location of buried unexploded ordnance. The analysis presented in subsection 3.2.2 indicates that the sensitivity of existing instruments is more than adequate for the task of detecting "standard" objects at "standard" depths. The difficulties inherent in applying these instruments in the field are related to their clutter sensitivity. It was noted that the amplitude of the magnetometric signature of a small object on the surface or at a shallow burial depth could be comparable to that of a larger, more deeply buried object. This behavior is a consequence of the inverse-cube dependence of signal amplitude on target depth.

Difficulties with clutter resulting from the presence of shrapnel or other metallic surface debris are to be expected in any subsurface UXO search of a former range or target area and are in no way unique to Kaho'olawe. Surface clutter should be thoroughly cleared from an area prior to beginning subsurface search operations.

Clutter associated with magnetic soils (such as the soils of volcanic origin found on Kaho'olawe) is not a universal feature of range clearance, but it is also not unique to Kaho'olawe. The effects of this form of clutter can be mitigated through improved magnetometer data collection and processing, specifically to take advantage of the known signature shape of compact buried targets. Advanced mathematical transform techniques for data and image processing could be applied to advantage in this processing and are now under active study by the authors.

Clutter of purely magnetic origin can be overcome by employing one or more complementary sensor techniques which do not respond to this form of clutter. Our assessment of the extant technologies indicates that electromagnetic induction—a technique less commonly used in UXO detection—would be an appropriate complement to magnetometry in subsurface UXO detection and location on Kaho'olawe.

3.4.3 Electromagnetic Induction

The first-order analysis presented in Section 3.2.3 suggests that electromagnetic induction is a viable method for detecting metallic subsurface UXO. We find that such sensors can produce large signal-to-noise ratios for the target sizes and depths of interest.

A significant problem with these sensors is their sensitivity to clutter. Our analysis suggests that the amplitude of the target signature will vary as r^{-6} where r is the range to the target. This dependence makes it easy for near-surface clutter to overwhelm the response of a deeply buried target. The applicability of induction-type sensors is also limited by their susceptibility to conductors of any kind. Hence, metallic surface debris, tree roots, and even highly conducting soil will produce a response in such instruments.

To date, it appears that there have been few attempts to identify buried objects using EM induction sensors. Attempts to do so based on spatial responses obtained with large loop sensors and with small imaging sensor arrays have met with limited success. Since the decay rate of the induced eddy currents depends on the size and shape of the objects in question, it is possible, in principle, for these sensors to exploit differences in measured decay rates to discriminate targets and clutter. There is, however, no evidence in the literature that such an approach has been investigated.

Our review of range clearance technology has identified relatively few uses of EM induction methods in UXO detection. The performance of commercially available metal detectors is severely hampered by their limited range and sensitivity, and the presence of surface clutter further degrades the performance of these devices. Our review of the literature produced only one example of an EM induction UXO detection system, although handheld EM induction detectors are commercially available.

We conclude that EM induction techniques are a feasible method for performing detection of buried UXO and that they would complement magnetometric techniques in that application. Although it is unlikely that an extant system is capable of providing acceptable detection performance in rugged terrain, the technology required to develop such a system has been demonstrated. It appears that relatively little research would be necessary to produce a useful UXO detection system based on this technology.

Chapter 4

A UXO Clearance Plan for Kaho'olawe

Hili hewa ka mana'o ke 'ole ke kūkākūkā.
Ideas run wild without discussion.
(Discussion brings ideas together into a plan.)

We come now to the final objective of this study: to develop a plan for the removal of unexploded ordnance from Kaho'olawe. Unfortunately, the only way in which an area can be *totally* cleared requires that the soil be excavated to a depth approximately equal to twice the greatest expected depth of penetration of the most deeply penetrating bomb or shell which was used in that area, sifted to remove all hazardous items, and finally replaced and stabilized. The monetary, and especially the environmental, costs of such an undertaking would be monumental.[1] Such measures do not, however, appear necessary for the clearance of Kaho'olawe: the land uses projected for the island can be accommodated by less drastic means. The clearance plan developed herein is tailored to these projected land uses, most of which, according to current Department of Defense guidelines, will require only surface and shallow subsurface clearance.

[1] The projected monetary cost of clearance of Kaho'olawe to a depth of 15 feet through excavation and soil processing was estimated in the Kistler study at $175M (1975 dollars), or approximately $400M today, using military equipment and labor. The environmental costs are incalculable.

We begin this chapter by reviewing the relationship between clearance requirements and projected land uses as articulated by the Department of Defense. After identifying and describing the land uses proposed for Kaho'olawe by Senate Bill 3088 and by the *Kaho'olawe Community Plan*, we determine the clearance requirements appropriate to those uses. The general procedures involved in the development of a clearance plan are described. We next present a proposed clearance plan for Kaho'olawe. We conclude with discussions of the clearance procedures to be employed, training programs for clearance crews, and related matters.

4.1 Clearance Requirements and Land Uses

There exist guidelines within the Department of Defense for relating projected land uses to UXO clearance requirements. It is important to note that these guidelines are not in any sense *standards*. While the development of clearance standards is under discussion within the Department of Defense, the base of knowledge and experience necessary to develop such standards does not presently exist. In this section we review these clearance guidelines and their relationships to possible future land uses on Kaho'olawe; we identify clearance requirements for Kaho'olawe based on these relationships. We begin by briefly reviewing clearance alternatives for Kaho'olawe.

4.1.1 Clearance Alternatives for Kaho'olawe

In this subsection we briefly identify and discuss the range of clearance alternatives available for Kaho'olawe. As in the Marinco study discussed in Chapter 1, these alternatives range from "no clearance" to deep excavations over wide areas. It is concluded that clearance in accordance with land-use planning will be the best approach.

One extreme option is to do nothing: that is, simply prohibit public access to the island for the foreseeable future. This "no-clearance" option has aspects which recommend it for consideration, including the fact that maintaining the image of Kaho'olawe as the "Island of Death" may discourage trespassers and protect the archaeological and historic sites from the depredations of pot-hunters and vandals. We believe, however, that it is really too late to consider this option. The island is regularly visited by the Protect Kaho'olawe 'Ohana and other groups, as well as by the military. Furthermore, we do not believe that this restrictive option would be acceptable to the State of Hawai'i. We do not consider this option further.

The option at the other extreme is to conduct large-scale, deep excavations over the entire surface of the island. This option will remove essentially all of the unexploded ordnance on Kaho'olawe; but the island's environment would be largely destroyed in the process. In addition, the monetary cost would probably be on the order of one billion dollars.[2] We do not consider this option further.

A "middle" option is to conduct a surface clearance of the entire island. Such a clearance would make the island suitable for such uses as a wilderness park or livestock grazing, and would permit limited human foot traffic. This option would not, however, be appropriate for more extensive human use or habitation, and it would not allow some of the land uses now under consideration for Kaho'olawe. While this option would be relatively inexpensive, it is also rather limiting, and we do not believe that it would be acceptable to the State of Hawai'i. We do not consider this option further.

There exist a variety of other "middle" options, in which varying degrees of clearance would be applied to different areas of the island. Selection of the appropriate option, in the view of the study team, should be based on future land uses. This matter is discussed in what follows.

4.1.2 General Considerations

The degree of UXO clearance required in a given area depends most strongly on the land use(s) contemplated for that area. Although standards for UXO clearance do not yet exist, much consideration has been given to the problem of quantifying the relationships between land uses and clearance requirements. One representation of these relationships, as described by the Navy [14], is shown in Table 4.1. It is evident that "degree of clearance" effectively translates to

[2]The Kistler study estimated a total cost of $400 million using military personnel and equipment. It is not possible accurately to convert this cost estimate into one appropriate for a civilian contractor, but an increase by a factor of two does not seem unreasonable.

Table 4.1: Land Uses and Clearance Requirements, I (adapted from [14]).

End Use	Clearance Requirement
Game refuge, disposal site, firing range, restricted area. Acceptable land uses may change over time.	Fence and post.
Wilderness parks, livestock grazing, limited human foot traffic.	Surface clearance.
Limited agriculture, tree farming, limited recreational vehicle use and foot traffic, parking areas, hunting, fishing.	Surface and shallow subsurface clearance to 18 inches.
Unlimited agriculture, tree farming, recreation. Limited construction (i.e., sheds, temporary buildings, pipelines).	Clearance to a depth of at least 10 feet.
Large structures, drilling mineral exploration, mining, etc. may be performed in areas cleared.	Remove all ordnance.

"depth of clearance." The cost of a clearance operation depends strongly on the required clearance depth.

An alternative representation of the relationships between land uses and clearance requirements, as proposed by the U. S. Army Corps of Engineers [78], is shown in Table 4.2. This table provides somewhat more detail than Table 4.1, and it also includes a very important provision: localized area clearance. This option requires that one carefully define the areas to be used for given purposes and match the clearance efforts to the intended land uses on a local basis.

There exist risks associated with any form of partial clearance. These include the following:

- Fence and Post "Clearance": The principal risk is encroachment on the fenced and posted area. In addition, there may arise a future clearance requirement before natural processes will render the area safe (and, as we have noted earlier in this report, this may take a very long time).

- Surface Clearance: Hazards may exist from items which are only shallowly buried. Furthermore, erosion by wind and water may expose items which were previously buried and not cleared.

Table 4.2: Land Uses and Clearance Requirements, II (adapted from [78]).

End Use	Clearance Requirement
Maintain current status as impact area or use for disposal area, weapons training site, firing range.	No clearance.
Wilderness park, dump area, cattle grazing (establish restriction on unauthorized excavation).	Surface clearance.
Limited agriculture, tree farming (establish restriction on unauthorized excavation).	Minimum depth clearance to 6 inches.
Farming, golf course, equipment parking (establish restriction on excavation below cleared depth).	Shallow depth clearance to 18 inches.
No land use restrictions provided clearance depth is maximum estimated depth of UXO penetration. If not, establish restriction on excavation below cleared depth.	Medium depth clearance to 15 feet and deep depth clearance to 20 feet.
Land-use as per above alternatives for appropriate depth. Localized clearance applies to building sizes, roads and excavation for utilities, etc. Restrict excavation to cleared area.	Localized area clearance.

- **Shallow Subsurface Clearance:** Erosion or excavation may expose ordnance below the originally cleared depth.
- **Deep Subsurface Clearance:** Erosion or excavation may expose ordnance below the cleared depth, although the erosion would have to be severe and/or the excavation deep.
- **"Complete" Clearance:** A missed item of ordnance might be encountered during deep excavation.

In determining possible future land uses for an ordnance-contaminated area, one must be aware of these risks. Formal risk-analysis procedures can be used to develop quantitative estimates of the risks [79].

4.1.3 Land Uses on Kaho'olawe

Senate Bill 3088 (101st Congress, Second Session) established the Kaho'olawe Island Conveyance Commission and charged it with recommending terms and conditions for returning the island of Kaho'olawe from the United States Government to the State of Hawai'i. Among the specific duties of the Commission were the following:

1. To identify any portions of the land surface of Kaho'olawe that are suitable for restoration to a condition reasonably safe for human habitation, including lands that are suitable for use by the State of Hawai'i for
   (a) parks (including educational and recreational purposes);
   (b) the study and preservation of archaeological sites and remains; and
   (c) the preservation of historic structures, sites, and remains; and
2. To identify any additional portions of such land that are suitable for restoration to a condition less than reasonably safe for human habitation, including lands that are suitable for
   (a) soil conservation and plant reforestation purposes; and
   (b) removal or destruction of non-native plants and animals.

The phrase "restoration of a portion of land to a condition reasonably safe for human habitation" includes, at a minimum, the removal or rendering harmless to activity of all hazardous or explosive ordnance located on or within such portion.

The land uses requiring restoration to a condition reasonably safe for human habitation involve the creation of a park (or parks) and the study and preservation of archaeological and historical sites. We have inferred from these uses that the specific areas which must be made reasonably safe for human habitation would include at least the following:

- a park headquarters area and its vicinity;
- roads, trails and camping areas; and
- the vicinities of the more important archaeological and historical sites[3].

Land uses not requiring restoration to a condition reasonably safe for human habitation are associated with soil conservation, planting and reforestation, and wildlife conservation. While such areas are not necessarily intended for human habitation, they must nevertheless be made reasonably safe for whatever human activities (such as grass and tree planting) are to be conducted thereon.

The *Kaho'olawe Community Plan* of Maui County [22] also sets forth projected land uses for Kaho'olawe. Land uses described in that plan include:

1. Establishment of permanent base camps (in which permanent structures such as *hālau*[4] may be constructed) in the following areas, as well as in others which may be suitable:
   (a) Honokanaia
   (b) Keanakeiki
   (c) Ahupu Bay
   (d) Hakioawa

[3]We have not attempted to identify any specific sites as being of greater interest or importance than any others.

[4]A *hālau* is a Hawaiian long house.

2. Establishment of temporary base camps (in which temporary shelters such as tents may be erected) in the following areas, as well as in others which may be suitable:
   (a) Honokoa
   (b) Kūhe'eia
   (c) Kanapou
   (d) Kamohio
   (e) Waikahalulu
   (f) Pu'u Moa'ulanui
3. Restricted uses in the former Target Area:
   (a) ordnance clearance
   (b) archaeological studies

These locations are indicated on the map of Kaho'olawe shown in Figure 1.2 and included in this chapter as Figure 4.1.

We view the land uses suggested in the *Kaho'olawe Community Plan* and those outlined in the Senate Bill as fundamentally similar (although, of course, not identical) and mutually consistent. These land uses imply certain UXO clearance requirements, which are discussed in the following subsection.

4.1.4 Clearance Requirements for Kaho'olawe

We have concluded from the information shown in Tables 4.1 and 4.2 and from the land uses proposed for Kaho'olawe which were described above that the minimum clearance requirements for the island are as follows:

1. Surface UXO should be cleared from as much of the entire island as possible and *must* be cleared from all areas to which people will have access;
2. Roads, trails, archaeological and historic sites, campsites, and other areas where people will gather should be cleared to a depth of at least 18 inches; and

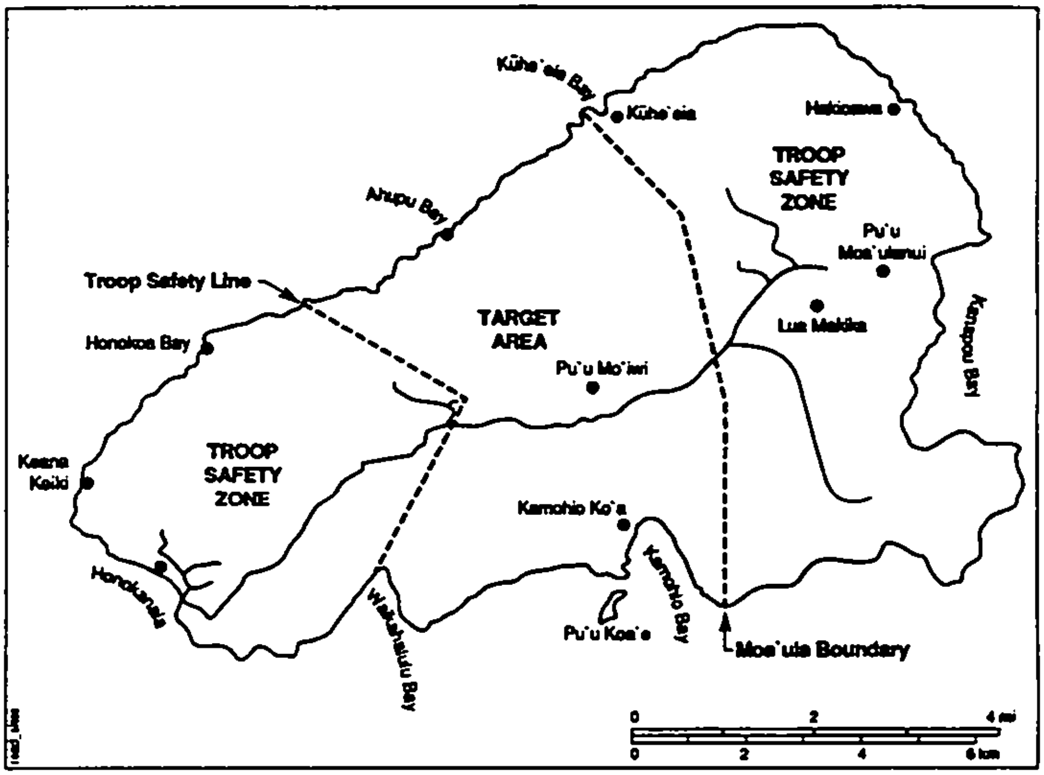

Figure 4.1: Map of Kaho'olawe.

3. "Deep" clearance will be required only at construction sites for permanent facilities.

We have also assumed that any excavations conducted at locations other than the construction sites for permanent facilities—for example, "digs" at historical or archaeological sites, or tree planting—would be carried out jointly with subsurface ordnance detection, location, and removal efforts at the sites involved, in order to ensure the safety of the individuals participating in the excavations.

4.2 Range Clearance Planning

In this section we discuss the process of clearing a range in general terms. The steps involved in this process are well defined and are described in detail in [14], upon which we have drawn extensively in preparing this part of the report. We also discuss the application of these steps to the development of a clearance plan for Kaho'olawe.

The overall clearance process involves five distinct but interactive functions. These are (1) *reconnaissance*, (2) *location*, (3) *clearance*, (4) *disposal*, and (5) *site restoration*. The first function, reconnaissance, involves the following activities:

- area designation;
- end use and clearance requirement definition;
- site survey;
- determination of cost and feasibility of clearance; and
- development of a detailed clearance plan.

The present study is devoted to the reconnaissance phase of the clearance of Kaho'olawe. The remaining four phases of the clearance process are briefly described below.

Location refers to the task of actually finding the ordnance, whether it lies on the surface of the ground or is buried beneath the surface. This subject has been discussed at some length in Chapter 3 of this report.

Clearance is the process of removing the ordnance found in the location process. It has been noted earlier that there exist two general types of clearance: *area recovery* and *point recovery*. Area recovery is considered to be most useful when the density of ordnance items exceeds approximately 1000 per acre. Point recovery relies heavily on detection and location technologies and is considered to be most useful when the ordnance item density is less than approximately 1000 per acre.

Disposal of the ordnance removed from the range follows. The ordnance may, if necessary, be detonated in place; or it may be removed to a separate disposal site for destruction or demilitarization.

Site Restoration is the process of recontouring the ground, replanting vegetation for soil stabilization, and performing related tasks to restore the environment of the (now cleared) range.

4.2.1 The Reconnaissance Phase

We now consider each of the activities involved in the reconnaissance phase of range clearance—from area designation to clearance planning—and comment on their application to the clearance of Kaho'olawe.

4.2.1.1 Area Designation

Area designation simply defines the actual area to be cleared. In the case of Kaho'olawe, the designated land area includes the entire island; but more refined area designations must also be developed in which clearance requirements are defined for various subareas of the island. This matter is discussed further in Section 4.3.

4.2.1.2 End Use and Clearance Requirement Definition

The relationship between end uses and clearance requirements was described earlier in this chapter. Proposed land uses and related clearance requirements for Kaho'olawe were also considered.

4.2.1.3 Site Survey

The site survey includes both library and field research to determine the ordnance history and the physical characteristics of the area(s) to be cleared, and to develop a clear understanding of any constraints which these characteristics will impose on clearance operations. A preliminary survey would include verifying the area location, establishing points of contact, obtaining range records, noting the types of terrain (indicated on the trafficability map in Figure 1.4) and vegetation (see Figure 1.3), and determining the general types and densities of ordnance contamination.

These activities have been conducted as part of the present study effort. A more comprehensive survey, which would typically be conducted (perhaps as a pilot project) prior to beginning the actual clearance operation, would also include surface and subsurface sweeps of selected subareas within the total area to be cleared.

4.2.1.4 Feasibility Determination and Cost Estimation

The area designation, the projected end uses and associated clearance requirements, and the site survey constitute the sources of the "technical" information needed to determine the feasibility and to estimate the cost of clearance. Additional nontechnical factors to be considered include the social impact of, and the environmental issues associated with, the clearance.

We believe that the social impact of clearing Kaho'olawe to enable the land uses discussed in the foregoing will be positive, if the clearance is accomplished in a manner which demonstrates respect for the Hawaiian concepts of *aloha*, *kōkua* (help, assistance), and *aloha 'āina*. In practical terms, this means that environmental damage caused by clearance operations should be minimized and that the island should be regarded as a living entity worthy of respect and care. In addition, local labor should be employed to the maximum extent possible.

4.2.1.5 Development of a Detailed Clearance Plan

This is the final step of the reconnaissance phase and is based on the results of the steps described in the foregoing. A proposed clearance plan for Kaho'olawe is described in Section 4.3.

4.2.2 Planning Constraints

We now review the possible constraints which might be imposed on clearance operations. We identify those constraints which we believe will impact operations on Kaho'olawe, as well as others which we believe to be of lesser importance in this instance (although they might be very important for other clearance operations). We indicate how the important constraints help to define and shape the structure of the clearance project.

4.2.2.1 Degree of Clearance Required

It has been noted earlier in this report that the degree of clearance required for a given area can be translated into a set of clearance depths which themselves depend on projected future land uses. There is no projected future use of Kaho'olawe of which we are aware that will require deep clearance of large areas. Surface and relatively shallow subsurface clearance of most of the island's surface will be sufficient to accommodate presently contemplated land uses.

4.2.2.2 Duration of the Clearance Project

Time constraints may be important for some clearance projects where there exists a need for the work to be completed by a given time, perhaps in order to allow a near-term land use. We assume that there is no such constraint on the duration of the clearance effort on Kaho'olawe. While the effort, once begun, should proceed in a timely manner, we see no need for the project to be completed in the immediate future. Thus we have assumed that a multi-year effort would be reasonable and acceptable to the Federal Government and the State of Hawai'i. We do recommend, however, that clearance operations begin as soon as possible. Recovery of the vegetation on Kaho'olawe will make clearance more difficult.

4.2.2.3 Size of the Clearance Team

The allowable size of the clearance team depends on several factors, the most obvious of which are the magnitude of the clearance effort to be performed and the time available for accomplishing it. An additional factor is the need for logistical support of the clearance team in the field. The present infrastructure on Kaho'olawe is adequate to support approximately 50 people, the majority of whom are military troops resident on the island for ten days each month. We assume that existing facilities could be expanded and upgraded relatively easily to accommodate approximately 120 people[5] permanently employed in the clearance effort; and we further assume that accommodating a much larger clearance team would require more infrastructure development than would be consonant with planned future land uses for Kaho'olawe.

4.2.2.4 Total and Annual Costs

The allowed total cost of a clearance project is an obvious constraint. In some cases, this cost will be driven by purely economic considerations, in the sense that the market value of the cleared land must be such as to justify the cost of clearing it. We do not believe that the total cost of the Kaho'olawe clearance is limited by such a consideration. On the other hand, the total cost must be in some sense "reasonable" and appropriate for the size of the area to be cleared.

The total cost of a clearance project, discounting inflation, is simply the cost per year times the duration of the effort in years, plus infrastructure costs. The latter are essentially fixed. As will be discussed in more detail later in this chapter, the annual cost of the planned clearance of Kaho'olawe will be in the range of $13–$16 million per year, exclusive of infrastructure development. The largest single component of this figure is labor cost, which is limited by constraining the number of project employees resident on the island, as was discussed above. We believe that this annual cost figure is both realistic and

[5]The size and composition of the resident clearance team are described in Section 4.3.6.

reasonable. The total cost, based on a five-year clearance effort, will be in the range \$70–\$75 million, or roughly \$2400–\$2500 per acre on average.

4.2.2.5 Environmental Considerations

Environmental constraints can be critically important in determining the allowable approaches to a given clearance project. The earlier Kistler [20] and Marinco [21] studies assumed no constraints of an environmental nature on clearance operations, and recommended mass excavation methods of clearance. Such methods inherently risk environmental damage through mechanisms such as increased soil erosion and soil deposition in surrounding marine areas. We have assumed that such environmental damage would be unacceptable in connection with the clearance of Kaho'olawe.

4.2.2.6 Constraints: Summary

The constraints discussed above help to define and shape the planning for UXO clearance from Kaho'olawe. Fortunately, they turn out to be mutually consistent: that is, potentially conflicting constraints do not appear to be present. For example, the limitation on the number of people resident on the island for the clearance effort (and the relatively low annual cost which results from the small size of the labor force) is consonant with the essentially unconstrained duration of the project. Furthermore, this limitation is consistent with the goal of minimizing the environmental burden on the island during the clearance. It is also consistent with the intended longer-term uses of the island as presently understood by the study team.

The total cost is primarily a function of the project duration. The project itself could be described as a longer-term and less intense effort (in terms of the number of people involved), rather than an all-out, short-term undertaking. We believe that the planned effort is consistent with the concept of care inherent in the Hawaiian term *aloha 'āina*.

4.3 A Proposed Clearance Plan

We describe our proposed clearance plan for Kaho'olawe in this section. We begin by presenting a top-level overview of the plan, followed by more detailed discussion of its implementation.

4.3.1 Overview of the Clearance Effort

We present a top-level overview of the planned three-phase clearance operation in this subsection. The clearance would be conducted by an on-site resident team of approximately 120 people. The three phases would require about five years for completion; a long-term "fourth phase" will also be needed, for reasons to be discussed below. In outline form, the operation would proceed as follows:

1. Phase I: Infrastructure Development
   (a) Clear and develop base facilities at Honokanaia (Smuggler's Cove);
   (b) Install boat and barge docking facility; and
   (c) Clear and improve network of roads and trails.
2. Phase II: Clearance of Selected Areas
   (a) Clear former targets (in the Target Area); and
   (b) Clear other areas, prioritized in accordance with planned uses (e.g., sites identified in the *Kaho'olawe Community Plan*, and important archaeological and historical sites).
3. Phase III: Broad Area Clearance
   (a) Clear broad areas having lower priority than those in Phase II; and
   (b) Clear areas where trafficability is difficult.
4. "Phase IV:" The Long Term
   (a) Continue UXO monitoring and conduct periodic spot checks;
   (b) Develop a dud ordnance reporting system; and

(c) Develop and conduct UXO awareness and safety programs for residents and visitors

We discuss each of these phases in the following.

4.3.2 Phase I: Infrastructure Development

In order to proceed with a clearance operation on the scale required for Kaho'olawe, one must be able to accommodate an essentially permanent resident labor force of some size. Given the approximately 120 individuals contemplated for this effort, and given that the facilities from which this force will work should be larger and of better quality than those currently used by the military, it follows that development of a base of operations and of transportation routes on the island should be the first order of business. We recommend that the base facility be located at Honokanaia, the site of the present military facility. This location can be supplied by air (helicopter) and, with provision of docking facilities, by water. (At present, the military camp can be supplied by water only in calm sea conditions. Addition of a dock would enable supply by water under a greater variety of sea conditions.)

Establishment of the base facility should build, to the maximum extent possible, upon the present military base at Honokanaia. Furthermore, and perhaps even more important, this establishment should be consistent with long-term use plans for the island. Thus, for example, if Kaho'olawe is intended to become a park (such as Pu'uhonua O Hōnaunau on Hawai'i) and perhaps a conference center (such as Asilomar in California), the base facility should be planned such that it would eventually become the park and conference center headquarters. The headquarters would include living spaces, dining facilities, laboratory facilities for visiting scholars, storage and maintenance buildings, and so on. All of these could serve in a modified role as base facilities during the clearance project.

Clearance and improvement of existing roads and trails, and development of more roads and trails as needed for the UXO clearance operation, should be conducted in parallel with the establishment of the base facility. In order for the UXO clearance to be efficient, it must be possible to transport crews from the base camp to the working area quickly and safely. Roads of reasonable quality will be required for this purpose. These same roads and trails would be used in the future to transport visitors or scholars around the island.

4.3.3 Phase II: Clearance of Selected Areas

Phase II clearance operations would build upon the base and road/trail network developed and cleared during Phase I by clearing a set of selected areas on the island. These areas will be of two principal types: (1) heavily contaminated areas (i.e., the former targets) and (2) specific areas desired for future land uses.

We recommend that the Phase II clearance begin with the former targets themselves, areas where the UXO contamination is heaviest and the vegetation is sparse. This view is based on our perception that these areas present the greatest potential risk.[6] Further, this prioritization will take advantage of the fact that clearance is greatly facilitated in the absence of vegetation (we note that the vegetation on Kaho'olawe is returning rapidly in many areas, as a result of the removal of the goat population). It will also accomplish the greatest clearance (by removing the largest number of potentially hazardous items) in the shortest time.

The Phase II effort should continue with the surface and shallow subsurface clearance of other selected areas, beginning with those which are less heavily vegetated and for which evolving land-use plans indicate a nearer-term desire for their clearance. The "permanent" and "temporary" areas which were identified in the *Kaho'olawe Community Plan* would be cleared with higher priority during this phase, as would the vicinities of the more important archaeological and historic sites.[7]

We assume that vegetation will ultimately return to most of the island. While revegetation is certainly desirable from many points of view, it is a hindrance to clearance operations. Therefore, for efficiency, the clearance should proceed in the less vegetated areas first. One is, in effect, in a race with Mother

[6] Every UXO item which is destroyed or removed reduces the potential for exposure, risk, and liability. The highest density of UXO items is expected at the former target sites.

[7] We have not attempted to identify which of these sites are more important than others; we assume, however, that of the several hundred such sites on Kaho'olawe, some fraction would be so identified.

Nature to clear unvegetated areas before they are re-covered. Clearance of vegetated areas may require cutting or controlled burning of brush and grasses and pruning of trees. These operations can be conducted in such a way as to cause little or no long-term environmental harm, especially if scheduled during the season when the vegetation is dormant or not so thick.

At the end of Phase II, Kaho'olawe will possess a cleared base or headquarters facility, a network of cleared roads and trails, and a set of cleared areas for campsites, archaeological and historical research, nature studies, reforestation, and related activities. A visitor could arrive on the island, travel on it via roads and trails, and visit a number of sites in safety. He or she would not yet, however, be able to leave this network and travel cross-country. Phase III of the clearance effort would enable such activities.

4.3.4 Phase III: Broad Area Clearance

The Phase III effort would constitute a continuation of the surface and shallow-subsurface clearance undertaken during the second phase, but would be directed toward the clearance of broad areas of lower priority than those which were identified above. We believe that essentially all of the land area on Kaho'olawe could be at least surface and shallow-subsurface cleared through Phase III. Roughly 10% of the island's surface area (the regions designated as "impractical" on the trafficability map of Figure 1.4) comprises steeply sloping regions which are difficult of access, either by clearance teams or by visitors to the island. These areas would be the most difficult to clear; their clearance would be undertaken toward the end of the project.

4.3.5 "Phase IV": The Long Term

We stress that *known perfect clearance cannot be practically achieved within the limitations of present and foreseeable technologies.* While it may be possible to remove all the surface and subsurface ordnance from a given area, it is not possible in general to *know* that all the ordnance has been removed. Furthermore, the effects of wind and water erosion can cause previously undetected, buried ordnance items to be revealed on the surface. Thus some residual risk of encounter with unexploded ordnance will exist even after formal clearance efforts have been concluded, and continuing UXO monitoring, awareness, and safety programs will have to be developed and put in place. This continuing monitoring effort can be considered to comprise the "fourth phase" of the clearance project.[8]

Permanent residents on Kaho'olawe (park rangers, for example) will need to be trained as UXO observers and provided with a means for marking found items for later removal by trained explosive ordnance disposal (EOD) personnel. Visitors to the island should be made aware of the possibility of encountering unexploded ordnance and informed of the risks associated with handling UXO items. They should also be made familiar with representative UXO items found on the island.[9] This familiarization might be accomplished with museum exhibits of demilitarized, inert UXO items in the park headquarters and an introductory video presentation which reviews the military history of the island, shows what some of the found UXO items look like *in situ*, and describes the clearance activities conducted or ongoing on Kaho'olawe. Such exhibits would serve as constant safety reminders for rangers and visitors alike.

4.3.6 Composition of the Clearance Team

The resident clearance team would comprise approximately 120 individuals organized into clearance and support groups. The labor categories and initial hourly wages of these individuals are shown in Table 4.3. We have based the wages of the members of the clearance team on those of individuals with similar qualifications in the Federal Civil Service. A premium of 25% has been added to compensate for (1) the higher cost of living in Hawai'i as compared to the mainland and (2) the relative remoteness of Kaho'olawe and the need to reside on the island on an essentially permanent basis.

The team would be organized as shown in the chart in Figure 4.2. The Kaho'olawe Ordnance Project Director would be in overall charge of the effort. He or she would manage and direct all phases of the clearance project,

[8]Many former World War II target practice areas and ranges were "cleared" immediately following the war, but were not monitored and rechecked thereafter. Therein lies a part of the reason for the accidents which have occurred at some of these sites.

[9]Ideally, visitors to Kaho'olawe would also be escorted by rangers when outside the park headquarters area and would not leave marked roads, trails, or campsites when hiking or exploring the island.

Table 4.3: Resident Clearance Team: Labor Categories and Wages.

(1) Number of Personnel	(2) Job Title	(3) Government Classification	(4) Hourly Rate [1]	(5) Hourly Rate (4) x 1.25 [2]	(6) Total Cost per Hour (1) x (5)
1	Archaeologist	GS-9	$13.55	$16.94	$16.94
2	Biologist	GS-9	13.55	16.94	33.88
1	Building Maintenance	WG-10	11.55	14.44	15.02
1	Carpenter	WG-10	11.55	14.44	15.02
1	Certified Industrial Hygienist	GS-12	19.66	24.58	24.58
1	Civil Engineer	GS-12	19.66	24.58	24.58
1	Contract Administrator	GS-9	13.55	16.94	16.94
2	Cook	WG-6	9.68	12.10	24.20
1	Data Analyst	GS-7	11.08	13.85	13.85
1	Draftsman/CAD	GS-5	8.95	11.19	11.19
1	Electronics Technician	GS-7	11.08	13.85	13.85
2	Emergency Medical Technician	GS-5	8.95	11.19	22.38
1	Environmental Engineer	GS-12	19.66	24.58	24.58
2	Heavy Equipment Operator	WG-10	11.55	14.44	28.88
20	Locator Operator	GS-5	8.95	11.19	223.80
1	Project Manager	GS-13	23.37	29.21	29.21
1	Nurse	GS-7	11.08	13.85	13.85
1	Project Director	GS-14	27.55	34.44	34.44
1	QC Supervisor	GS-11	16.40	20.50	20.50
1	Rodman	GS-7	11.08	13.85	13.85
1	Safety Engineer	GS-12	19.66	24.58	24.58
1	Secretary	GS-5	8.95	11.19	11.19
1	Security Guard	GS-2	6.44	8.05	8.05
10	Senior UXO Specialist	GS-12	19.66	24.58	245.80
1	Site Safety and Health Officer	GS-12	19.66	24.58	24.58
1	Support Director	GS-13	23.37	29.21	29.21
1	Support Manager	GS-12	19.66	24.58	24.58
1	Surveyor	GS-9	13.55	16.94	16.94
1	Technical Writer	GS-9	13.55	16.94	16.94
3	Truck Driver (heavy)	WG-8	10.60	13.25	39.75
6	Truck Driver (light)	WG-6	9.68	12.10	72.60
1	Typist	GS-3	7.12	8.90	8.90
5	UXO Specialist	GS-11	16.40	20.50	102.50
5	UXO Technician	GS-9	13.55	16.94	84.70
40	Unskilled Laborer	WG-3	8.30	10.38	415.20
1	Vehicle Maintenance	WG-10	11.55	14.44	14.44
122	Total Direct Labor Cost per Hour				$1761.50

[1] Current U.S. Government Civil Service rate
[2] Cost of Living Allowance (COLA) for Hawaii = 1.25

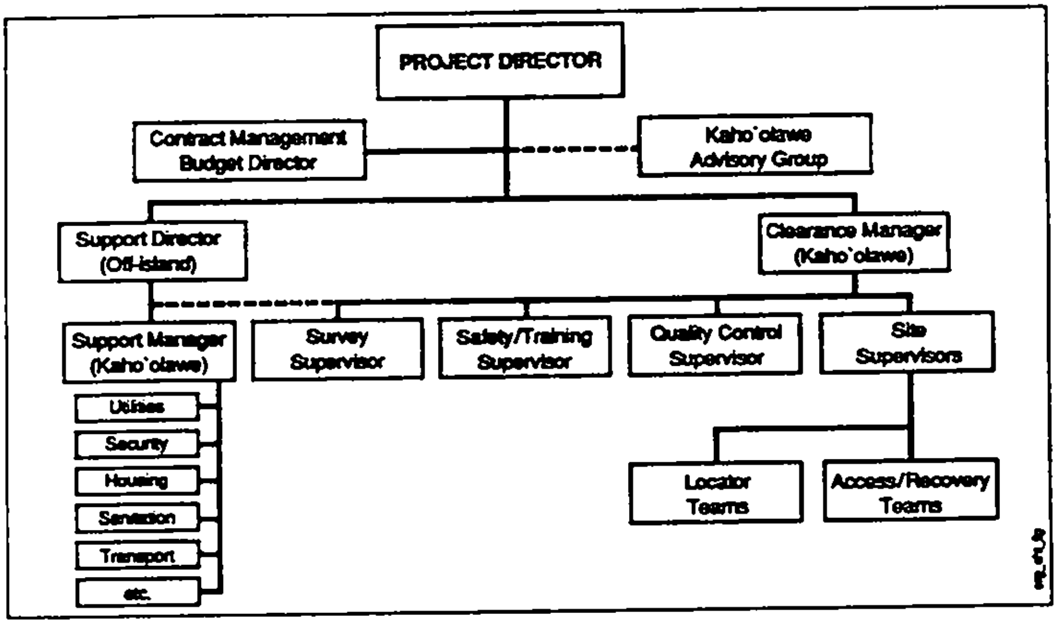

Figure 4.2: Organization of the clearance team.

and would coordinate the project with other activities on Kaho'olawe. The Kaho'olawe Advisory Group, which would provide the vehicle for this coordination, would comprise individuals concerned with archaeology, biology, history, and other aspects of the rehabilitation of Kaho'olawe. This group would not be part of the clearance team *per se*, but its existence is assumed; it is discussed further in subsection 4.4.2. The Project Support Director (PSD), who would be based off-island, would manage and coordinate all activities associated with the logistical support of the clearance team, including fuel, food, water, housing, transportation, and so on. The PSD would report to the Kaho'olawe Ordnance Project Director. On-island logistics would be the responsibility of the Project Support Manager, who would report to the Project Support Director.

On-island oversight and management of the ordnance clearance effort itself would be the responsibility of the Clearance Project Manager. He or she would oversee the site survey, safety and training, and quality assurance and control efforts, and would provide overall management of the clearance teams (locator and access/recovery teams) in the field. Field supervision of the locator teams and the access and recovery teams would be handled by Site Supervisors. The activities of these latter groups are described more fully in Section 4.4.

The Survey Supervisor would be responsible for laying out the UXO search grid system on Kaho'olawe and maintaining records of progress of the clearance effort. He or she would maintain the UXO-related Geographical Information System for the project.

The Safety and Training Supervisor would be responsible for on-island safety programs, UXO recognition and handling, locator and access/recovery training and certification.

The Quality Control Supervisor would be responsible for quality assurance of the clearance effort. He or she would establish and implement QA/QC procedures, including random spot checks of cleared areas.

4.3.7 Cost and Schedule

The number and the hourly wages of individuals in each job category were shown in Table 4.3. The total unloaded hourly rate for the resident clearance team will be \$1849.58 (a factor of 1.05 larger than the figure in Table 4.3, to account for the fact that the project start date will be at least a year hence). We apply a burden factor of 2.5,[10] yielding a total loaded hourly rate of $4623.94. Multiplying this figure by 2080, the number of working hours per year, we obtain a total burdened labor cost of $9,617,790 for the first year of the project.

Operating costs are estimated at $2,000,000 for the first year, roughly 20% of the loaded labor cost. These costs include transportation, fuel, water, spares, equipment replacement, batteries, communications equipment, food shipment, medical supplies, and other items. An additional planning and startup cost of $1,000,000 is associated with the first year of the effort.

Adding labor, operating, and (10%) contingency costs for the first year, we obtain a total cost of $13,879,569. Based on a five-year project duration (to be discussed below) and an assumed 5% inflation rate, we arrive at a total project cost of $71,715,185 exclusive of infrastructure costs (the startup cost is not included in the out-year cost estimates). This cost breakdown is shown in Figure 4.3.

The planned five-year duration of the clearance project is based on the size of the clearance team and on historical data for clearance rates. We have assumed that the average clearance rate per locator and access/recovery team is 1.5 acres per day. With 20 such teams in the field, a total area to be cleared of 29,000 acres, and 220 working days per year,[11] we obtain a project duration of 4.4 years. Adding additional time for project planning, startup, and shutdown, we obtain a total project duration of approximately five years. An "operations and maintenance" effort (the "fourth phase" of the clearance, referred to above) would be put into place after the clearance itself was completed. This effort, which would include periodic UXO surveys of randomly selected areas on Kaho'olawe and disposal of any found UXO items, would cost in the neighborhood of one million (1992) dollars annually and would taper off gradually over the next five to ten years.

[10]This estimated burden rate is based on industry averages.

[11]The number of paid hours per year is 2080, or 260 paid days. Reducing this figure by 15% for vacation and holidays, we obtain 221 actual working days per year.

LABOR	RATE
Total Hourly Wage Rate	$1,762
Economic Factor	5%
Burden Rate	2.50
Fully Burdened Hourly Wage Rate	$4,624
Annualized	2,080
Total Labor Cost	$9,617,790
OPERATING EXPENSES	$2,000,000
Annual Operating Expenses	$1,000,000
Start-Up Planning Costs	

Annual Costs	Year 1	Year 2	Year 3	Year 4	Year 5	TOTAL
Labor	$9,617,790	$10,098,680	$10,603,613	$11,133,794	$11,690,484	$53,144,361
Operating Expenses	$2,000,000	$2,100,000	$2,205,000	$2,315,250	$2,431,012	$11,051,262
Start-Up Costs	$1,000,000	$0	$0	$0	$0	$1,000,000
Subtotal All Costs	$12,617,790	$12,198,680	$12,808,613	$13,449,044	$14,121,496	$65,195,623
10% Miscellaneous	$1,261,779	$1,219,868	$1,280,861	$1,344,904	$1,412,150	$6,519,562
Total Annual Costs	$13,879,569	$13,418,548	$14,089,474	$14,793,948	$15,533,646	$71,715,185

Figure 4.3: Project cost breakdown.

4.4 Clearance Procedures

The procedures to be followed "on the ground" in the clearance itself are discussed in this section. Specific plans and procedures which must be developed before the actual clearance can begin are also identified. A key feature in the planned clearance is *separation of functions* of the various groups working in the field. This separation will enhance both the efficiency and the safety of the clearance operation.

The first step to be performed upon commencement of the project is to survey and grid the island into small (two meter) squares. Not all of these need be marked with stakes at the same time (the number of stakes would be quite large), but it must be possible to identify exactly in which square[12] one is located at a given time. This gridding would focus the search for UXO items into small areas of manageable size. Subsets of grid squares would be selected for each phase of the clearance effort: for example, in Phase I, those grid squares in the vicinity of Honokanaia and along the roads and trails would be identified and marked.

The selected subset of grid squares for each clearance phase would then be separated into four or five subareas. These subareas should be separated as widely as possible. A staging site for scrap, a storage site for inert salvageable materials, and a disposal site for explosive items which need not be detonated in place would be identified and established in each subarea.

The actual clearance would begin with a thorough surface clearance of every grid square in each subarea. The goal of this effort is to remove all ordnance, shrapnel, and scrap lying on the ground surface, thereby yielding a "clean" environment for later subsurface search operations. Ordnance which can be moved would be taken to the disposal site for destruction or demilitarization. Ordnance which cannot be moved would be detonated in place, with measures taken, wherever possible, to limit the scattering of shrapnel and debris in order to avoid contributing to the surface clutter in the area.

After a subarea has been thoroughly surface cleared, the locator crews would search the subarea—one grid square at a time—using magnetometers and electromagnetic induction (EMI) detectors. The locator crews would mark "hits"

[12]There will be approximately 35 million such squares covering the entire island.

using golf balls, nonmetallic weights with ribbons, or similar means. Where possible, magnetometric and/or EMI data would be recorded using data loggers and archived for later off-line computer processing. It is important to note that the locator crews would not stop to dig out detected items: their function is only to mark the locations of suspected items.

Access and recovery of the suspected items found by the locator crews follows. Digging by hand using pick and shovel, or using a small backhoe, the access and recovery crews check each suspected item. If an explosive object is found which cannot be removed, it is marked for later detonation in place (the access and recovery crews would not detonate the ordnance in place). If the item can be removed, it is taken by the access and recovery team to the identified disposal site.

The process outlined in the foregoing would be followed throughout the project. It would be modified for the clearance of the vicinity of the base camp, because of the need for deeper excavation there. It is not known at the present time what sort of architecture will be selected for the base camp/park headquarters facility. We will assume for the purpose of the present discussion that the buildings would be built in the style of a Hawaiian long house or *hālau* using "pole house" construction methods. A pole house structure is supported above the ground on a series of deeply sunken posts. The deep excavation associated with the construction of a pole house is the digging of the post holes. This excavation would be conducted in tandem with borehole UXO detection to ensure that hazardous items, if encountered, are detected and safely removed (or, if necessary, detonated in place).

4.4.1 Quality Assurance and Control

Quality assurance and quality control of the clearance effort must be an integral part of the project. Quality assurance normally involves testing the cleared area against a standard. It was noted earlier that clearance standards do not yet exist. The procedure now used by the U. S. Government for quality assurance of a sponsored clearance project is as follows:

1. Identify a subset of cleared areas within the clearance project for quality-assurance testing;

2. Employ the best available detection technology[13] to perform 100% inspection of the selected areas; and

3. Accept no failures (that is, passing the quality-assurance test requires that *no* explosive item be found within the test areas).

This quality-assurance procedure should be employed throughout the clearance effort for periodic spot checks, and at intervals during the post-clearance ("Phase IV") UXO monitoring program.

4.4.2 Project Coordination

The ordnance-clearance project should not be considered as an operation independent of other activities to be conducted on Kaho'olawe, which include archaeological and historical studies, nature studies, reforestation, and so on. Thus we recommend that a top-level "Kaho'olawe Advisory Group" be formed to coordinate all these activities. The need for such coordination is indicated by the following possibilities, all of which involve the ordnance-clearance effort:

- The ordnance-clearance team encounters buried bones or other artifacts in its search of a given area. Coordination with an archaeologist is called for.

- The ordnance-clearance team plans to work in an area scheduled for reforestation. Coordination with tree-planting teams will be required.

- The ordnance-clearance team needs to remove vegetation from a given area as part of the clearance of that area. Coordination with a botanist will be necessary.

In each case, consultation and coordination will be required to ensure that one effort does not interfere with another—indeed, one would attempt to ensure that the ordnance clearance project supported other efforts where possible.

[13] Which of the several available technologies is "best" will generally depend on the characteristics of the site.

4.4.3 Training Programs for On-Site Crews

It is not necessary that everyone directly involved in the clearance effort be EOD-qualified (that is to say, a graduate of the Naval Explosive Ordnance Technology Center's EOD School). A number of such individuals will be needed on the resident clearance team to identify found ordnance items and to maintain and enforce the site safety plan. It is necessary, however, that everyone on the resident clearance team be trained in certain skills, as required by his or her job. Everyone working on the island should be made familiar with the military history of Kaho'olawe, the kinds of ordnance items which will be found there, and the hazards associated with improper handling of these items. Everyone working on the island should have basic first aid and CPR training. Everyone should also know proper marking procedures for ordnance items which they may inadvertently encounter. Individuals who will be working as locator crew members will need to be trained in the physical principles of locator operation and in the use of the locators themselves. These individuals will have to take and pass a "qualifying course" wherein they must successfully locate real UXO objects which have been buried at known locations and depths. Individuals who will be working on access and recovery teams must be trained in the proper methods for excavation of potentially hazardous items.

4.4.4 Plans and Procedures

A number of plans and procedures must be developed before the beginning of any clearance operation. These are listed, and briefly discussed where appropriate, in this subsection. They include:

- Master Work Plan for the entire effort;
- UXO Operating Plans detailing the approaches, methods, and operational procedures to be employed at each site;
- Safety, Health, and Emergency Response Plan, including staff organization, hazard communication and training, medical surveillance, exposure monitoring, health and safety equipment, and standard operating procedures;

- Accident Prevention Plan;
- Archaeological Encounter Procedures for dealing with suspected archaeological finds; and
- Quality Control Plan for the application of quality-assurance procedures.

These plans should be developed and in place prior to beginning clearance operations on the ground. The Master Work Plan, in particular, should be developed in detail before the project begins. Success in overall, detailed planning will help to ensure success of the project itself.

4.4.5 The On-Site Clearance Community

Because of Kaho'olawe's relative isolation, the clearance team would reside on the island, at least during the work week. Because of the size of the team, and because its members would all live near Honokanaia, a community of not insignificant size would be established. The proper functioning of this community should be facilitated by every possible means. The authors are neither sociologists nor town planners, but we wish to point out some factors which should be considered in planning the clearance effort. They include:

- A "plantation store" and post office should be established on a self-supporting basis.
- A volunteer fire department should be formed from members of the community.
- A sheriff or other police officer will be needed for law enforcement.
- Recreational facilities should be available for after-hours use by the resident clearance team.
- High school (GED) or community-college courses should be available for continuing education.
- Facilities for religious observances (probably temporary modifications of existing base-camp facilities) will be needed.

- Communications facilities for routine and emergency use must be available.
- Transportation to and from the island should be provided on a private, self-supporting basis.

These matters and many more must be addressed before the clearance effort begins. Because Kaho'olawe is in many ways a remote site, the island will not be simply a workplace for the members of the clearance team. It will be their home for the duration of the project.

Chapter 5

Conclusions and Recommendations

In this report we have reviewed the circumstances which have led to the need for an assessment of the degree of unexploded ordnance contamination on Kaho'olawe, an assessment of the technologies which could be useful in detecting and locating buried unexploded ordnance, and a plan to clear unexploded ordnance from the island. We have presented estimates for the degree of UXO contamination on Kaho'olawe and inferred from those estimates that point recovery will be the preferred approach to clearing UXO from the island. Point recovery relies on detection and location technologies for its success. We have assessed these technologies and judged their potential utility for application to the clearance of Kaho'olawe.

We have reviewed the projected land uses described in Senate Bill 3088 and in the *Kaho'olawe Community Plan* and have described the requirements for clearance of surface and subsurface unexploded ordnance as presently articulated by the Department of Defense. Relating projected land uses to these clearance requirements, we developed a set of clearance requirements specifically for Kaho'olawe and we presented a proposed clearance plan. Our conclusions and recommendations follow.

5.1 Conclusions

The "bottom line" of the study effort is summarized as follows:

- Kaho'olawe can be cleared of UXO to the degree required by present land-use plans for the island. The clearance can be accomplished by a resident clearance team of approximately 120 people over a period of about five years. The relatively small size of the team will minimize the environmental burden associated with the clearance effort.

- The cost of the clearance will lie in the range $70M–$75M, exclusive of the cost of infrastructure development. Such development should be planned and implemented in accordance with the planned future uses of Kaho'olawe.

- Because of the residual risk of exposure to UXO which can result from imperfect clearance and/or from exposure of previously buried UXO items by the action of wind and water, continuing awareness and safety programs will need to be developed and implemented for Kaho'olawe's permanent residents and visitors.

The problem of clearing surface and buried/subsurface unexploded ordnance from Kaho'olawe, while not trivial, can be dealt with. Indeed, circumstances related both to Kaho'olawe's military history and to its planned future uses are in many ways ideal for the rehabilitation of the island, if the decision is made to proceed with clearance of the unexploded ordnance. In particular,

- Kaho'olawe has been used only as a target range; it has not been a war zone. Thus
  - The residual explosive hazard on Kaho'olawe is the result of *failures to detonate as intended* of items fired or dropped on the island.
  - There is no evidence of hazard due to chemical weapons on the island.
  - The island has not been sown with mines, which are *intended* to detonate when disturbed.

- Planned land uses imply only very limited development and a degree of control over visitor access to, and exploration on, the island. This control will contribute greatly to the safety of residents and visitors alike.

UXO contamination, like some diseases, cannot always be completely cured without killing the patient. It can, however, be reduced and managed, and contaminated lands—like Kaho'olawe—can be brought back to an acceptable degree of safety and utility while the restorative forces of nature work to permanently heal their wounds.

5.2 Recommendations

5.2.1 Detection and Location Technology Development

The research necessary to develop a new technology is often costly and time consuming. For the clearance of an area the size of Kaho'olawe, however, a research program which leads to enhanced UXO detection systems could be very cost effective, even when such a program is of substantial size. For this reason we recommend that research be done to improve the performance of several sensor technologies. Specific recommendations are as follows:

- In the survey of Chapter 3 we concluded that the technologies of ground-penetrating radar (GPR), magnetometry, and electromagnetic induction were reasonably mature and well understood. Unfortunately, many of the sensors based on these methods which are available at this time have been developed primarily for use in laboratory settings. *We recommend that research be undertaken to develop instruments based on these technologies which are portable, rugged, and better suited for use in rough terrain.*

- A problem encountered in all of the detection methods examined in Chapter 3 is clutter. In many remote sensing systems, the effects of clutter can be reduced through a judicious use of signal processing. Moreover, the cost of incorporating such processing is often minimal. *We recommend that signal processing methods be investigated for use in improving the data quality of the sensors noted above.*

- Many groups have an interest in detecting concealed objects, and UXO detection technologies can benefit from many of these developments. The fields of explosive detection (e.g., airport security, mine detection), non-destructive testing, and various forms of remote sensing are of particular interest. *We recommend that surveys of recent developments in related fields be conducted before clearance operations commence and while they are underway to insure that the most cost-effective means of UXO detection are employed.*

Finally, we specifically recommend against the development of new technologies, and against research to substantially extend the capabilities of existing systems, unless compelling technical reasons for such work can be identified. The review presented in Chapter 3 suggests that while many sensors are theoretically capable of detecting buried UXO, few systems can actually detect these objects because of variability in the natural environment.

5.2.2 UXO Clearance of Kaho'olawe

Our recommendations regarding the clearance of Kaho'olawe are summarized as follows:

- Because of the increasing difficulty of clearing areas in which the vegetation is recovering, the clearance should begin as soon as possible and should be initially focused on those areas where the vegetation has not yet recovered.

- The sensors identified herein are complementary to a degree and, hence, by using them in combination one can achieve a substantial improvement in detection capability. *We recommend that clearance operations not rely exclusively on a single type of sensor.*

- Because a clearance effort on the scale of Kaho'olawe has never before been undertaken, a pilot project should be conducted on a representative set of subareas on the island. The total area included under the pilot project should be between 500 and 1000 acres and should be representive of the three principal vegetation types (scrub, woodland, and barren) and various types of terrain.

We strongly believe that a pilot project on Kaho'olawe would be of great value in validating (or correcting) the ordnance contamination estimates, the technology assessments, and the clearance plan developed herein. The planning basis for a full-scale clearance project would be immeasurably strengthened by incorporating the experience obtained from a pilot project.

Finally, we note that Kaho'olawe, because of its size, relative isolation, and lack of substantial development and population, could be an ideal site for research into improved methods for detection, location, removal, and destruction or demilitarization of unexploded ordnance, and for training in the operational use of UXO remediation techniques. Thus we recommend that the clearance of Kaho'olawe be viewed as an opportunity to develop and improve techniques and skills which could be employed in other UXO remediation efforts, both within the United States and abroad. Foreign participation in these activities should be encouraged.

Appendix A

Executive Order No. 10436

President Eisenhower's Executive Order No. 10436 of February 20, 1953 reserved the island of Kaho'olawe for naval purposes and placed it under the jurisdiction of the Secretary of the Navy. It also discusses the rehabilitation of the island when it is no longer needed for naval purposes. The Executive Order is transcribed below. Note especially the provisions in Section 4.

EXECUTIVE ORDER 10436

RESERVING KAHOOLAWE ISLAND, TERRITORY OF HAWAII, FOR THE USE OF THE UNITED STATES FOR NAVAL PURPOSES AND PLACING IT UNDER THE JURISDICTION OF THE SECRETARY OF THE NAVY

WHEREAS it appears necessary and in the public interest that the Island of Kahoolawe, Territory of Hawaii, which comprises an area of approximately forty-five square miles, and which forms a part of the public lands ceded and transferred to the United States by the Republic of Hawaii under the joint resolution of annexation of July 7, 1898, 30 Stat. 750, be taken and reserved for the use of the United States for naval purposes, except that portion comprising an area of 23.3 acres, more or less, heretofore taken for lighthouse purposes by Proclamation No. 1827 of the President of the United States dated February 3, 1928 (45 Stat. 2937); and

WHEREAS it is deemed desirable and in the public interest that provision be made for the conducting of a program of soil conservation on the island while the reservation made hereby is in force, and that the area within such reservation be restored to a condition reasonably safe for human habitation when it is no longer needed for naval purposes:

NOW, THEREFORE, by virtue of the authority vested in me by section 91 of the act of April 30, 1900, 31 Stat. 159, as amended by section 7 of the act of May 27, 1910, 36 Stat. 447, it is ordered as follows:

1. The Island of Kahoolawe, Territory of Hawaii, except that portion taken by the United States for lighthouse purposes by Proclamation No. 1827 of February 3, 1928, is hereby taken and reserved for the use of the United States for naval purposes, and is placed under the jurisdiction of the Secretary of the Navy.

2. The Secretary of the Navy shall, within a reasonable period following the date of this order, eradicate from the island all cloven-hooved animals, or shall within such period and at all times thereafter while the area hereby reserved or any portion thereof is under his jurisdiction take such steps as may be necessary to assure that the number of such animals on the island at any given time shall not exceed two hundred.

3. The Territory of Hawaii shall have the right, at its expense and risk, at reasonable intervals to enter and inspect the island to ascertain the extent of forest cover, erosion, and animal life thereon, and to sow or plant suitable grasses and plants under a program of soil conservation: Provided, that such entrance and inspection shall not interfere unreasonably with activities of the Department of the Navy or of the United States Coast Guard.

4. When there is no longer a need for the use of the area hereby reserved, or any portion thereof, for naval purposes of the United States, the Department of the Navy shall so notify the Territory of Hawaii, and shall, upon reasonable request of the Territory, render such area, or such portion thereof, reasonably safe for human habitation, without cost to the Territory.

DWIGHT D. EISENHOWER

The White House,
February 20, 1953.

Appendix B

World War II Target Ranges in Hawai'i

World War II brought an American military presence to Hawai'i on a much larger scale than had existed there prior to the Japanese attack on Pearl Harbor. The need for training grounds and base facilities led to the acquisition and development of many sites throughout the Hawaiian Islands for these purposes. By the end of the war, the Army and Navy (including the Marine Corps) owned, or held temporary possession of, approximately 390,000 acres in Hawai'i. The island of O'ahu alone had 50 sizable Army reservations and 26 Naval stations [24, pp. 221, 222]. Kaho'olawe was the only island wholly devoted to military activities, but all of the eight major Hawaiian islands, including even Ni'ihau, felt the military presence to some degree.

Some of these sites were used as impact areas for artillery, bombing, and naval gunfire. They were located on, or offshore of, Hawai'i, Maui, Lāna'i, Moloka'i, O'ahu, Kaua'i, and Kaho'olawe, and on some offshore islets, particularly Mānana (Rabbit Island), off O'ahu; Molokini, off Maui; Mōkapu and Mokuho'oniki, off Moloka'i; and Ka'ula, southwest of Ni'ihau. Many of these sites were cleared to some extent after the war; but incidents which have occurred since, warnings that have appeared in newpaper articles, and on-site inspections by members of the study team indicate that there is significant residual UXO contamination throughout Hawai'i. The problem on Kaho'olawe is by no means unique to that island.

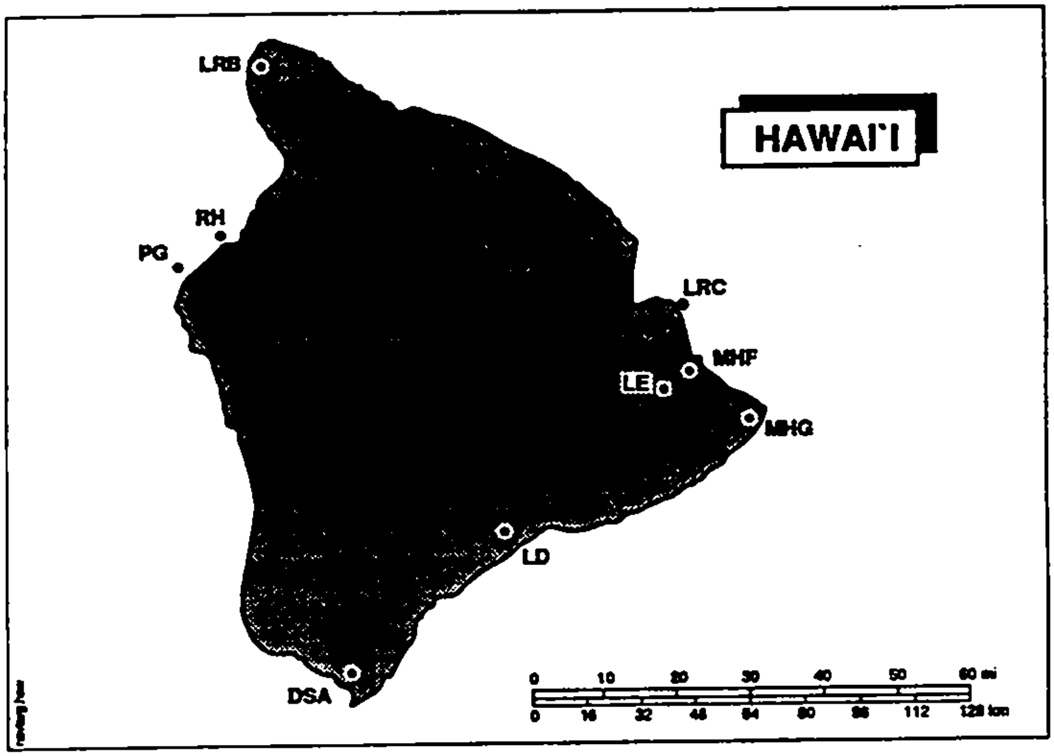

Figure B.1: World War II Navy targets: Hawai'i.

B.1 Survey of Target Sites in Hawai'i

Hawai'i

A map showing the locations of World War II Navy targets on and near the island of Hawai'i in 1945 is given in Figure B.1. These locations are taken from [80]. The targets and the types of ammunition expended on them are briefly described below.

- LRB, LRC: *Rocket ranges.* Sub-caliber aircraft rockets (SCARS); high-explosive rockets (LRB only).

- MHF, MHG: *Masthead targets.* Miniature and water-filled bombs.[1]
- LD, LE: *Marked land targets.* Miniature and water-filled bombs; live-load bombs, rockets, strafing (LD only).
- RH: *Moored radar target.* Miniature bombs.
- DSA: *Dummy seaplane base.* Miniature and water-filled bombs; live-load bombs, SCARS, strafing.
- PG: *Moored pyramid target.* Miniature and water-filled bombs.

Other areas on Hawai'i that were used as ranges and impact areas include the Ka'ū Bombing Range Military Reservation, comprising about 3,000 acres in the southwestern portion of Hawai'i Volcanoes National Park [81]. This site was a bombing and air gunnery range from July 1940 until June 1950. Some 91,000 acres of the Parker Ranch were used for artillery practice. The Panini range was located south of Kohala Ranch, near Ka Lae in the Ka'ū district. Figure B.2 shows a map of World War II training and impact areas on the island of Hawai'i.

Maui

A map showing the locations of Navy targets near and on Maui in 1945 is shown in Figure B.3 [80]. These targets are briefly described below.

- MB, MC: *Mining drill areas.* Miniature and water-filled bombs.
- LG: *Marked land target.* Miniature and water-filled bombs.
- LRD: *Rocket range.* high-explosive rockets and SCARS.
- IC: *Rock target* (Molokini). Miniature, water-filled, and live-load bombs; strafing; rockets.
- RG: *Moored radar target.* Miniature bombs.

[1]Water-filled bombs contain no explosive. Miniature (practice) bombs are equipped with an explosive cartridge for spotting purposes.

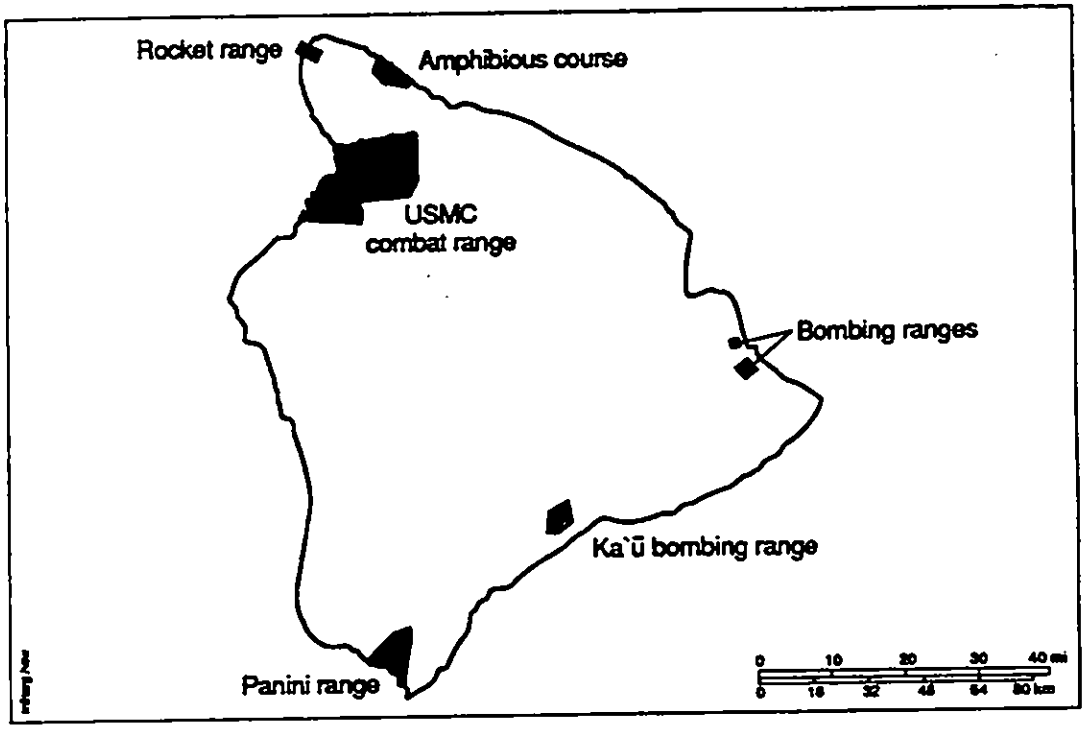

Figure B.2: World War II impact areas on Hawai'i.

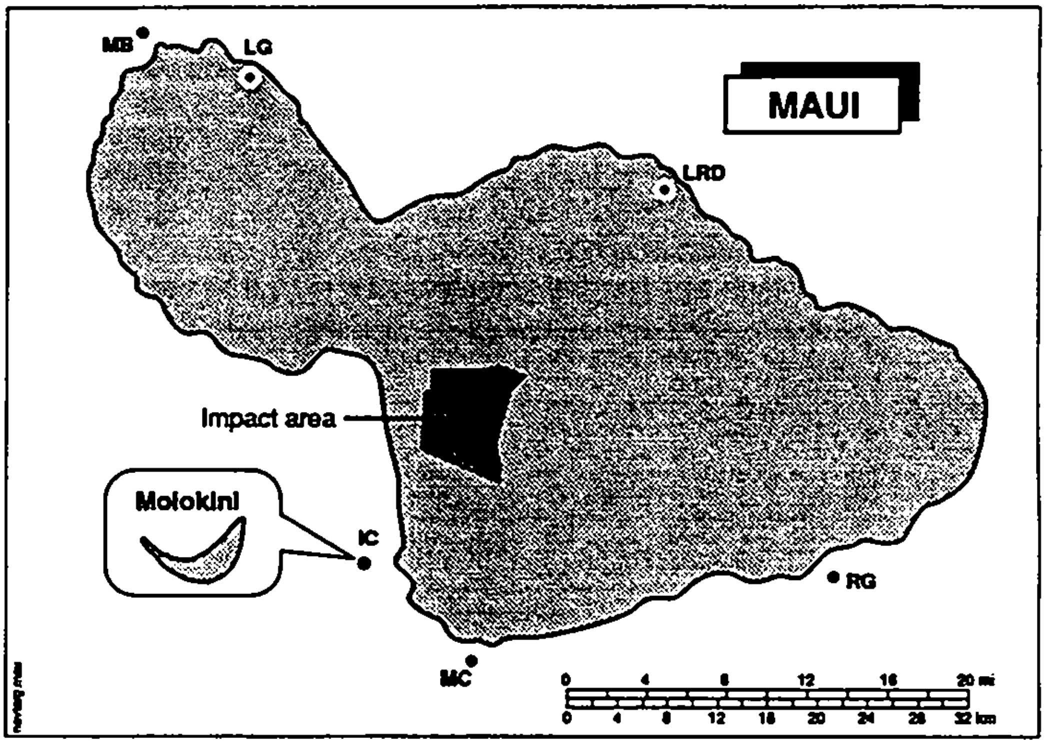

Figure B.3: World War II impact area and Navy targets: Maui.

Maui also had a number of training areas on the island itself. Porteus [25] has provided a partial description:

> "But four thousand feet down [from the top of Haleakala], at the foot of the mountain, was an arid red waste of kiawes and prickly pear which the Marines used as an artillery practice range, alight at night with green tracer bullets and the glow of exploding shells" [25, p. 9].
>
> "This is part of the Harold Rice ranch and his cattle live on kiawe beans and prickly pear. It was this area that was made into an artillery range for the Army and Marine divisions, with rather heavy casualties among the cattle which later learned to avoid the fields of heaviest fire" [25, p. 252].
>
> "You could be waiting for your plane at the civilian airstrip and watch the heavy shells throwing up red geysers of dirt in almost ceaseless gun practice on the range at the foot of Haleakala" [25, p. 263].

The location of this impact area on Maui is shown on the map in Figure B.3.

Lāna'i

The Navy used six targets on or just offshore of Lāna'i. The locations of these targets in 1945 are shown on the map in Figure B.4 [80] and described in the following.

- PD, PE: *Moored pyramid targets*. Miniature and water-filled bombs.
- MHE: *Moored masthead target*. Miniature and water-filled bombs.
- LF: *Marked land target*. Miniature and water-filled bombs.
- MA: *Mining drill area*. Miniature and water-filled bombs.
- RF: *Moored radar target*. Miniature bombs.

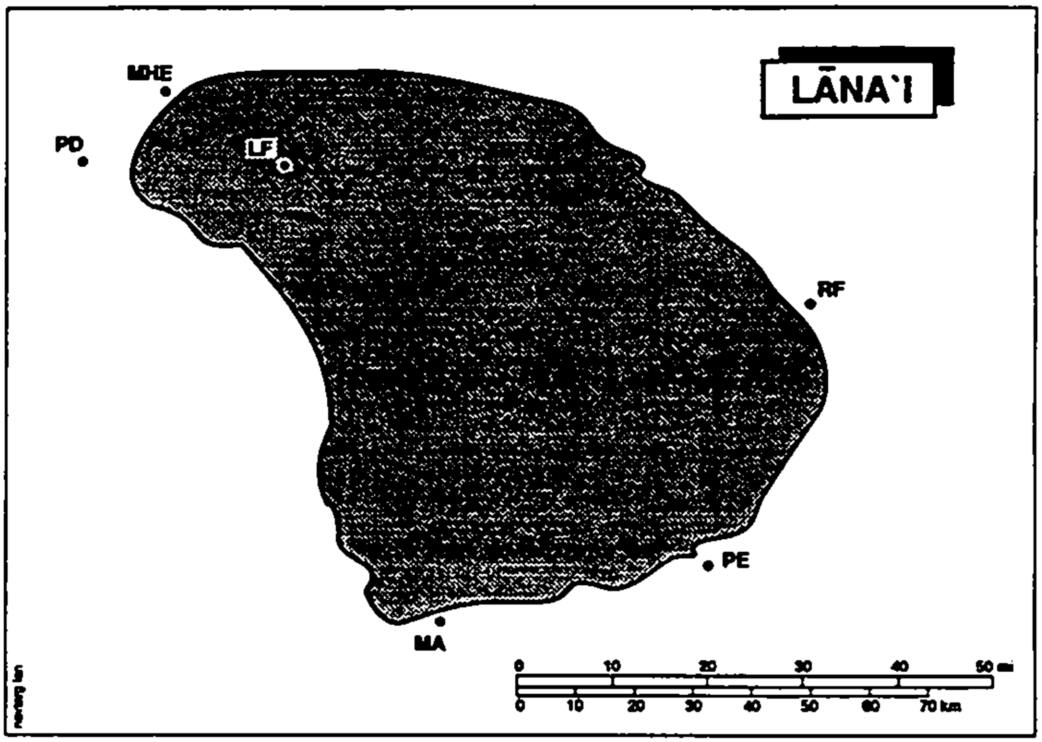

Figure B.4: World War II Navy targets: Lāna'i.

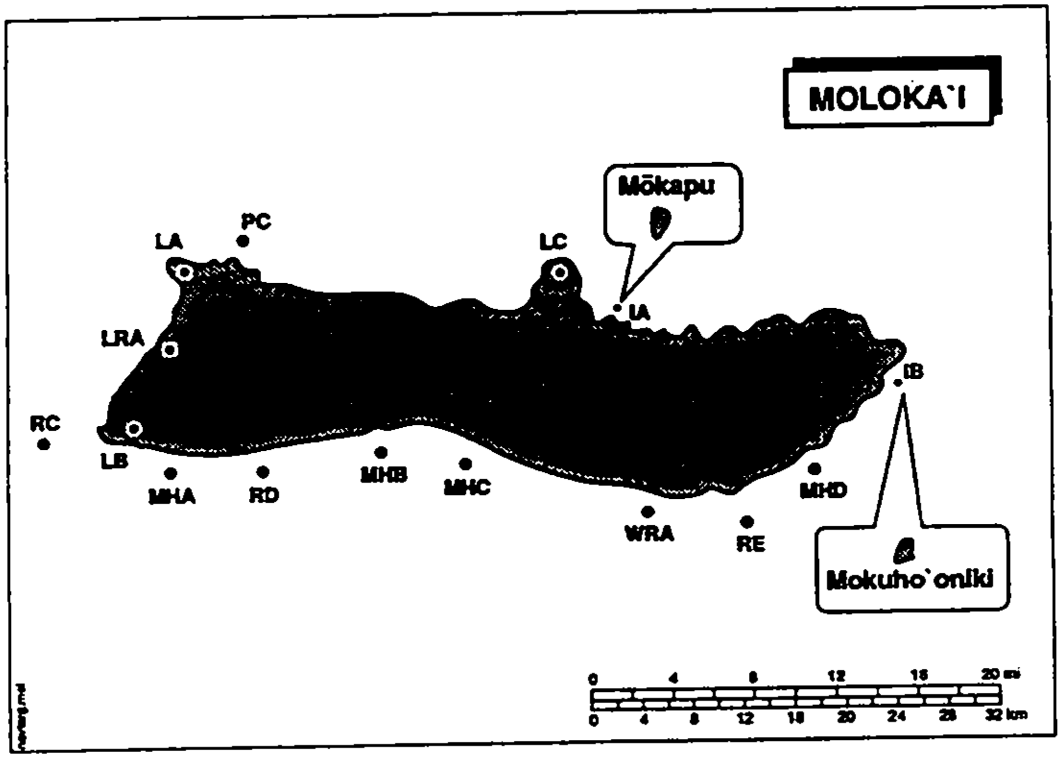

Figure B.5: World War II Navy targets: Moloka'i.

Moloka'i

A map showing the locations of Navy targets on Moloka'i in 1945 is shown in Figure B.5 [80]. These targets are briefly described below.

- LA, LB, LC: *Marked land targets.* Miniature and water-filled bombs; SCARS (LB); live-load bombs, strafing, high-explosive rockets (LA).
- MHA, MHB, MHC, MHD: *Moored masthead targets.* Miniature and water-filled bombs.
- RC, RD, RE: *Moored radar targets.* Miniature bombs; water-filled bombs (RE).

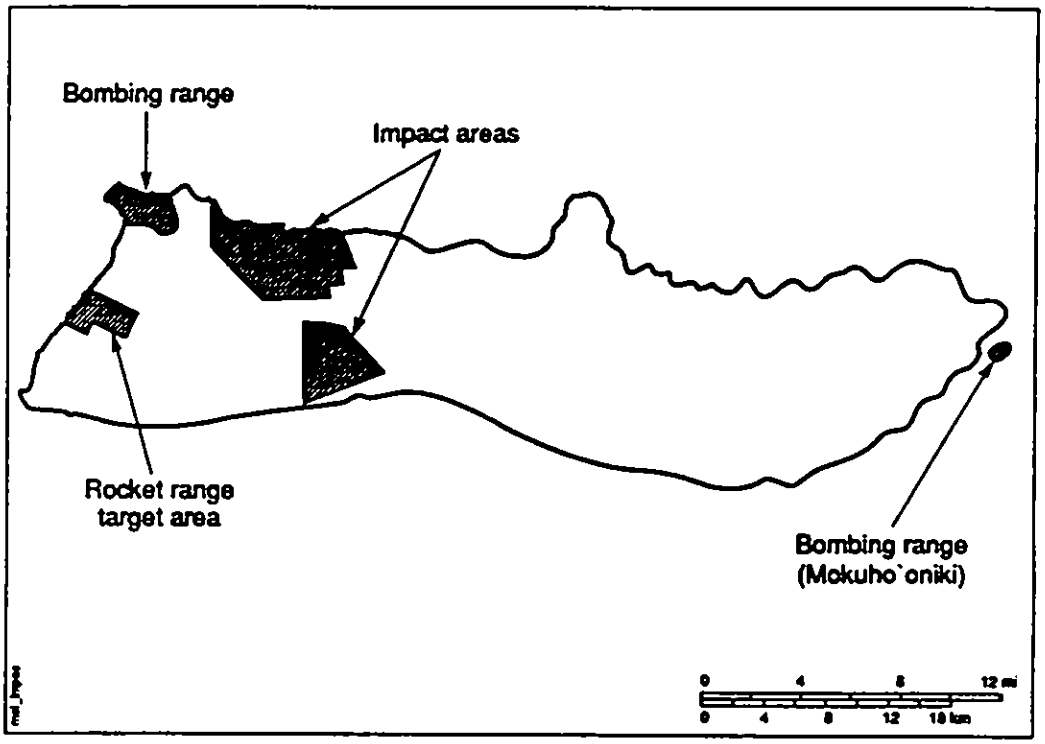

Figure B.6: World War II ranges and impact areas on Moloka'i.

- IA, IB: *Rock targets* (Mōkapu and Mokuho'oniki respectively). Miniature and water-filled bombs; strafing.
- PC: *Moored pyramid target.* Miniature and water-filled bombs.
- LRA: *Rocket range.* High-explosive rockets and SCARS.
- WRA: *Water rocket range.* High-explosive rockets and SCARS.

A map showing World War II ranges and impact areas on Moloka'i is shown in Figure B.6.

O'ahu

Two Navy targets were situated near O'ahu in 1945. These targets are briefly described below.

- DB: *Moored pyramid target*, located off Ka'ena Point. Miniature and water-filled bombs.
- RB: *Moored radar target*, located off Nānākuli. Miniature bombs.

While there existed only two Navy targets near O'ahu—and these were both moored offshore—training areas, camps, and centers, and ranges and impact areas, were scattered over the surface of the island. The Navy targets and the impact areas on O'ahu are shown on the map in Figure B.7. The Makua Range on Leeward O'ahu is still used by the Army for live-firing practice. The Schofield facility is, of course, active.

Kaua'i and Ni'ihau

One World War II Navy target was located near Kaua'i and another near Ni'ihau in 1945. These targets are listed below.

- PA: *Moored pyramid target*, off Maka o Kaha'i Point. Miniature and water-filled bombs.
- RA: *Moored radar target*, off Ka'ula, southwest of Ni'ihau. Miniature bombs.

Kaua'i was the site of four artillery impact areas: Anahola-Moloa'a, Wailua, Waimea, and Grove Farm. In addition, Kaua'i contained four jungle training areas; 33 pistol, rifle, and machine gun ranges; infiltration, bayonet, close-combat, and grenade courses; a combat-in-cities training area; and more. A map of the jungle training and artillery impact areas is shown in Figure B.8 [82].

Kaho'olawe

The island of Kaho'olawe was considered in Chapter 2. We note that the Navy maintained three main targets on the island during World War II: a moored

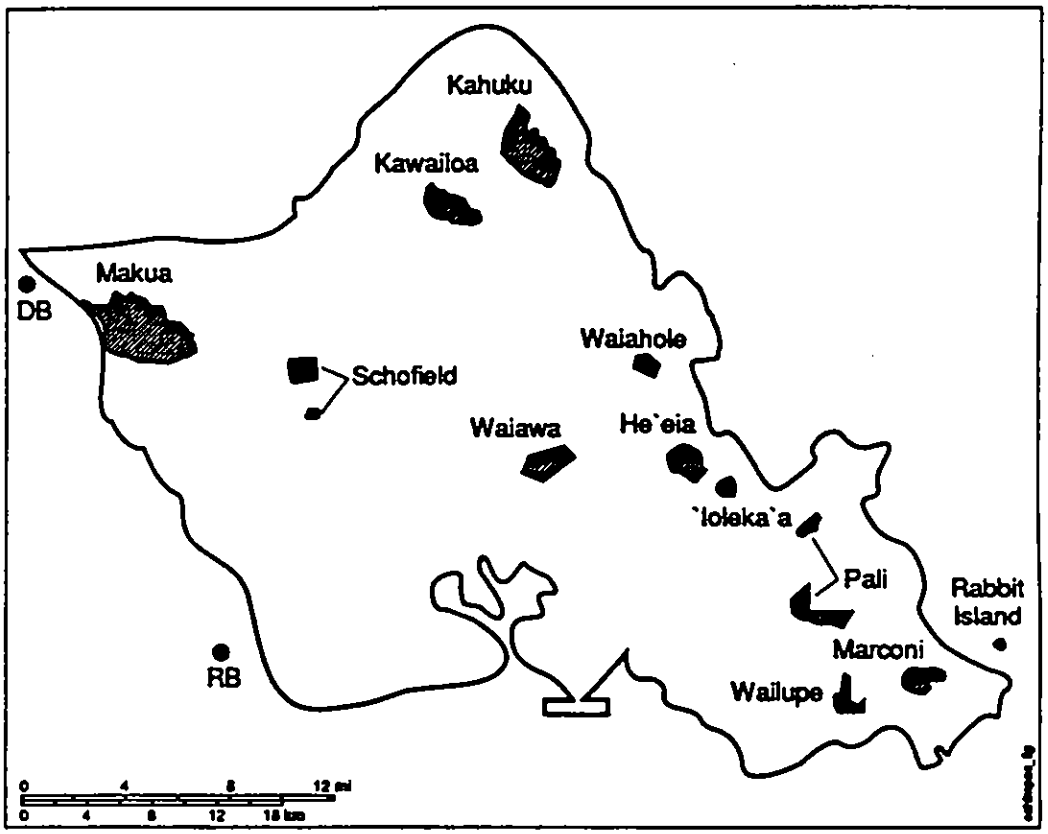

Figure B.7: Impact areas and World War II Navy targets: O'ahu (only Schofield and Makua are presently active).

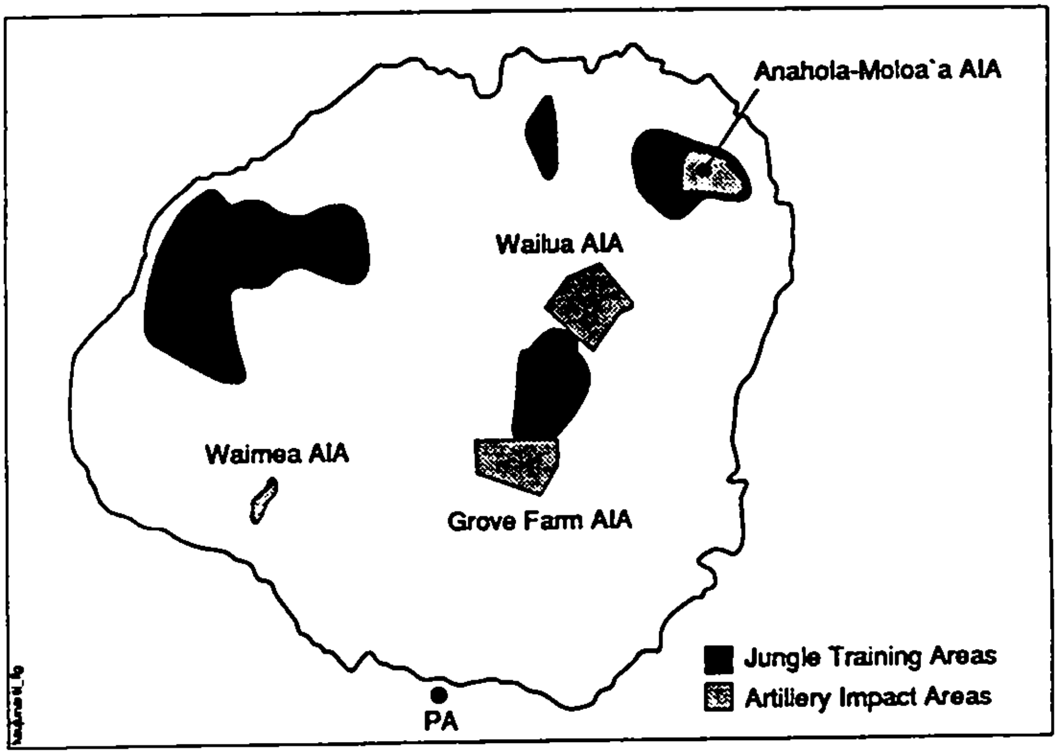

Figure B.8: World War II jungle training and artillery impact areas on Kaua'i. The location of Navy target PA is also indicated.

pyramid target off the northwestern shore; an air-support target complex; and a dummy airfield.

B.2 The Post-World War II Period

At the end of World War II, many of the military personnel who had been stationed in Hawaiʻi left for home or for occupation duty in Europe and Japan. Many of the camps and training areas were deserted within a few months after the end of the war, except for "demolition squads combing ranges for unexploded bombs and shells" [24, p. 367]. That the postwar cleanup efforts were less than completely successful is evidenced by two incidents. In the first, a child was killed on Kauaʻi shortly after the war "when a shell she found near Knudsen Gap exploded in her hand" [82]. Reference to Figure B.8 shows the Knudsen's Gap Training Area and the Grove Farm Artillery Impact Area just to the north. In the second, a minor named Russell Iokepa died in May 1954 on Hawaiʻi as a result of injuries he suffered when a dud shell exploded on the Parker Ranch. It will be recalled that some 91,000 acres of the ranch were used as a firing range during the war.

Searches of newspaper records have revealed several articles dealing with discoveries of—and accidents associated with—unexploded ordnance in Hawaiʻi and with warnings from military authorities concerning hiking in certain formerly used range areas.

One member of the study team (Donaldson) has visited over 30 formerly used range sites in Hawaiʻi (roughly half of the total number of such sites in Hawaiʻi) during the past few years, in connection with unexploded ordnance surveys and clearance operations for the U. S. government and private landowners. Unexploded ordnance items have been found on all of the sites visited.

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