LIGO Technical Report

TR-87-1

FINAL REPORT OF THE LIGO SITE SELECTION WORKING GROUP

J. Livas, P. Saulson, R. Spero, K. Thorne

24 August 1987

LIGO-T870002-00-D

Issued 04 April 89

FINAL REPORT OF THE LIGO SITE SELECTION WORKING GROUP

Jeff Livas, Peter Saulson, Bob Spero, Kip Thorne

MIT and Caltech, 24 August 1987

The primary goal of our site selection working group has been to identify and quantify the scientific issues relevant to the selection of a pair of sites for the Laser Interferometer Gravitational Wave Observatory (LIGO).

This final report is organized into three sections plus appendices. Section I describes the scientific issues that we have identified and studied, and our conclusions about them. Section II discusses the implications of these issues for specific sites, with emphasis on Edwards Air Force Base California, Columbia Maine, INEL Idaho, and LSU Louisiana. Section III summarizes our recommendations. Backup information, including the detailed justification for a number of assertions made in the body of the report, is relegated to Appendices.

I. THE SCIENTIFIC ISSUES

A. The Observables

The LIGO project is not just a single experiment. We anticipate that, after the initial discovery of gravitational waves, the LIGO will be used as the pioneering observatory to launch a new branch of astronomy. It therefore is important to understand exactly what is observable and how to connect the observables with quantities of astrophysical interest.

The observables are the time series $\Delta L_j(t)/L_j$ which represent the fractional path length differences as a function of time for the various antennas (labeled j). We shall also regard as observables the time delay between gravity-wave arrivals at each pair of antennas, $\Delta t_{i,j}$, which one infers by comparing the time series $\Delta L_i(t)/L_i$ and $\Delta L_j(t)/L_j$.

For a periodic or burst source the full information available at earth, all of which is astrophysically important, is contained in two numbers, the direction (θ,ϕ) from the earth to the source, and two dimensionless functions of time, $h_+(t)$ and $h_\times(t)$, which represent the waveforms of two orthogonal polarization states + and ×. For a stochastic background the full information available is contained in two functions of frequency f, and direction (θ,ϕ): $\tilde{h}_+(f,\theta,\phi)$ and $\tilde{h}_\times(f,\theta,\phi)$, which represent the square roots of the spectral densities of h_+ and $h_\times$, and which have dimensions $\mathrm{Hz}^{-1/2}$; however, on theoretical grounds it seems highly unlikely that the background will be polarized (that $\tilde{h}_+$ will differ from $\tilde{h}_\times$) and somewhat unlikely that, in the frequency band of earth-based detectors $f \gtrsim 10\mathrm{Hz}$, it will be direction dependent, i.e. anisotropic. Thus it is that one normally characterizes the background by a single function of frequency, $\tilde{h}(f)$ with dimensions $\mathrm{Hz}^{-1/2}$.

In its initial configuration of one detector at each of two sites, the LIGO will provide observers with two time series $\Delta L_1(t)/L_1$ and $\Delta L_2(t)/L_2$, and from those series one time delay $\Delta t_{1,2}$. Regardless of where the sites are located and how the detectors are oriented, these are insufficient data from which to extract the full information available in gravitational-wave bursts or in an anisotropic background (though, if the signal-to-noise is high, they are sufficient for full information about periodic gravitational waves; see discussion in Appendix E). Full information for bursts and for an anisotropic, polarization-dependent background will require combined data from at least four detectors and preferably four different sites (see Appendix E), and thus – depending on the status of detectors elsewhere in the world – will likely require a LIGO upgrade. Thus it is that our study of site issues has focussed not only on the roles of the sites in the initial, two-detector, gravity-wave search configuration (Subsection B below), but also on their roles in possible future upgrades (Subsection C below).

B. The Initial, Two-Site, Two-Detector Configuration

1. Goals

If we (and the world's other groups) fail to discover gravitational waves within five to ten years of LIGO turn-on, we may never get an upgrade for further searching and may in fact all get shut down and the field go dormant for a long time. Therefore, it is our view that the initial LIGO configuration, including sites, must be one which comes close to optimizing the probability of successfully discovering gravitational waves – even though (see below) that may mean a significant reduction in the amount of information extractable from the waves. To the extent, and only to the extent, that it can be done without *much* compromising the probability of discovery, the initial design should be adjusted to optimize information extraction and optimize suitability for future upgrades. The key phrase here is "without *much* compromising". One's interpretation of *"much" can significantly influence the choice of LIGO configuration, including sites. After considerable calculation, thought, and discussion, we have agreed that a reduction in amplitude signal-to-noise ratio σ by less than 10 per cent is an acceptable compromise of the probability of discovery, if one thereby obtains a substantial increase in the information extracted from the waves or in suitability for future upgrades.* For reasons explained in Appendix A, some committee members regard a reduction of σ in excess of 10 per cent as unacceptable.

2. Relative Orientation of the Two Initial Detectors

If gravitational waves are linearly polarized and the sources are isotropic on the sky, then the overall signal-to-noise ratio σ in our two-detector search will be maximized by choosing the detectors' orientations so as to maximize the overlap of their beam patterns. Stan Whitcomb (1985) has determined by numerical experiments the resulting, optimal orientation for an Edwards detector which is paired with a Columbia detector with the orientation dictated by Columbia topography (see Appendix B for details), and Bernard Schutz and Massimo Tinto (1987, Fig. 12a) have replicated Stan's conclusion. One can show that for Columbia-Edwards, and for any other pair of sites in the contiguous United States (where the sites' planes intersect at angles $\beta<40$ degrees), this optimal orientation is well approximated by the following rule: *When the two detectors are projected onto the plane that bisects their two planes, the directions of their legs should coincide, modulo rotations of* 90 *degrees.* We shall call this the "coincident-projection orientation". It is optimal for gravity-wave discovery because it makes the polarization states to which the two detectors are sensitive as nearly the same as possible, independently of the direction to the source. Of course, this optimality for discovery is bought at the price of a near total loss of information about the wave form in the other polarization state.

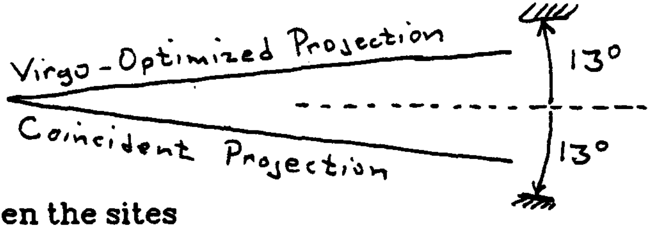
Deviations of relative orientation from coincident-projection can be as large as 18 degrees, but no larger, if one is to keep the overall σ within 10 per cent of its maximum (our avowed goal), and no larger than 13 degrees if one is to keep σ within 5 per cent of its maximum.

One might worry that the overall σ would be more than 10 per cent sensitive to the detectors' absolute orientation relative to the line of intersection of their planes, and that this might rule out the Columbia site with its fixed orientation. Not so: Fig. 12(a) of Schutz and Tinto (1987) shows that, for Columbia-Edwards (the largest separation feasible in the contiguous United States), changes in absolute orientation affect the direction-averaged rms σ (essentially the square root of the quantity plotted by Schutz and Tinto) at only the two per cent level; and one can show analytically that, for sources in directions that give the optimal σ, changes in absolute orientation affect σ only by fractional amounts of order $.25\beta^4 \lesssim 0.05$, where $\beta \lesssim .65$radians$\cong$38degrees is the angle between the detectors' planes. Thus the absolute orientation is unimportant.

The above conclusions rely on the assumption of linearly polarized waves. Massimo Tinto (1987a, and Appendix C of 1987b) shows that the optimal relative orientation is essentially the same (coincident projection) for elliptically polarized waves as for linearly polarized waves, but that the overall sensitivity σ is much less affected in the elliptical case by deviations from coincident projection. On this basis, and because he believes on general theoretical grounds that the strongest sources will involve substantial rotation and will thus produce elliptical waves, Schutz (private communication) has argued that we should consider *not* choosing the coincident-projection orientation for our first pair of detectors. By choosing, instead, the "45-rotated orientation" (projections of antennas on bisector plane rotated 45-degrees to each other), one would obtain good sensitivity to both wave forms $h_+(t)$ and $h_\times(t)$ and thus gain significantly greater information from the waves, at the price of less than 10 per cent loss of σ for typical elliptically polarized sources. We believe that this suggestion relies dangerously much on the assumption of elliptical polarization. While elliptical polarization is theorists' best guess for the strongest of the sources, it is not a high-confidence guess; and if it is wrong, the sources are likely to be weaker than otherwise, leaving us desparate for every bit of sensitivity we can get. If we opt for the 45-rotated orientation and the theorists' best guess is wrong, then we will have to live with an overall σ that is 40% less than we would have had with the coincident-projection orientation — a dangerously large penalty in view of the analysis in Appendix A. Thus it is that we strongly recommend coincident-projection orientation.

The above conclusions also rely on the assumption of isotropic sources. The most reasonable alternative assumption is sources in the Virgo cluster of galaxies. However, Schutz and Tinto (their Fig. 11a) have shown for Edwards and Columbia that the Virgo-optimized relative orientation differs by only 10 degrees from the isotropic-optimized, coincident-projection orientation; and such a 10-degree difference affects the overall σ by less than 5 per cent. For detectors closer together than Edwards and Columbia, the difference between Virgo-optimization and isotropic-optimization will be even less.

To conclude: In order to achieve an overall σ within 5 per cent of the maximum for both Virgo sources and isotropically distributed sources, we recommend the coincident-projection orientation to within an error box of width ±13 degrees centered on the average of coincident projection and Virgo-optimized projections. The absolute orientation within this constraint is not important.



3. Distance between the sites

It is important, for secure removal of non-Gaussian noise, that the two sites be much father apart than the correlation lengths of various noise sources that can affect the detectors. Some relevant correlation lengths are listed in Appendix C. Likely disturbances that might give false coincidences, such as tiny earthquakes or cosmic ray air showers, are strongly correlated over distances of about one kilometer, but may have weak correlations over much greater distances. Noise in electrical transmission lines may be correlated over distances of order 150 km, though this is a highly uncertain number and an unlikely source of false coincidences. We suggest for safety that the separation between sites be constrained to $D \gtrsim 300$ km, though this is a very flaky recommendation that deserves further study if it becomes an important issue. (Below we shall argue for $D \gtrsim 2500$ km in order to get good angular positions on sources.)

As the two sites are pushed farther and farther apart, the earth's curvature will force their antennas' beam patterns to overlap less and less, thereby reducing the overall signal-to-noise ratio σ. In Appendix D it is shown that, for sources distributed uniformly in space, half the sources observed by a single detector will lie within an angle $\theta_{1/2} \cong 35$ degrees of overhead or underfoot. Within these regions the detector's amplitude sensitivity (beam pattern function) drops off with angle θ from the vertical as $\cos\theta$. Correspondingly, for two antennas whose verticals differ by an angle β, the overall sensitivity to a source which has vertical angles $\theta+\beta/2 \lesssim \theta_{1/2}$ at one detector and $\theta-\beta/2 \lesssim \theta_{1/2}$ at the other will vary with β as

$$\frac{\sigma(\beta)}{\sigma(0)} \simeq \frac{[\cos^2(\theta+{}^1\!/\!_2\beta)+\cos^2(\theta-{}^1\!/\!_2\beta)]^{1/2}}{[2\cos^2(\theta)]^{1/2}} \cong 1-\frac{1}{8}\beta^2 \ . \tag{1}$$

This simple calculation shows that the loss of overall sensitivity due to the earth's curvature making the two detectors lie in different planes is

$$\frac{\Delta\sigma}{\sigma} \simeq \frac{1}{8}\beta^2 = 0.05\left[\frac{D}{4200\mathrm{km}}\right]^2 , \tag{2}$$

where D is the distance between sites and 4200 km is the Edwards-Columbia separation. Thus, in terms of beam-pattern overlap, all separations within the contiguous United States are acceptable.

When searching for a stochastic background via cross-correlation of the output of the two detectors, the limits one can place on $\Omega_{GW}(f) \equiv$(energy density in gravitational waves at frequency f and in bandwidth $\Delta f = f$)/(energy density to close the universe) vary with D as follows: (i) For $D \lesssim c/f = (300\mathrm{km})(f/1\mathrm{kHz})^{-1}$ the limits are independent of D. (ii) For $D \gtrsim c/f$ the limits become worse with increasing D as

$$\frac{\Omega_{\mathrm{GW,D}}}{\Omega_{\mathrm{GW,0}}} \simeq \sqrt{fD/c} \simeq 4 \left(\frac{f}{1000\mathrm{Hz}} \right)^{1/2} \left(\frac{D}{4000\mathrm{km}} \right)^{1/2} . \tag{3}$$

Here $\Omega_{\mathrm{GW,D}}$ is the limit obtained with the detectors a distance D apart; $\Omega_{\mathrm{GW,0}}$ is the limit with the detectors side by side. If we believed that stochastic background is a moderately likely source for first detection, this would suggest D not much larger than the minimum distance for decorrelated noise at the two sites. However, (i) it seems to us very unlikely that stochastic background will be the first source detected; and (ii) since the best sensitivity of the LIGO detectors to Ω_{GW} is likely to be at frequencies $f \lesssim 100$ Hz (see Fig. 1.5 of our last joint proposal for the design study), it is likely that the sensitivity to stochastic background will start falling off only at $D \simeq 3000$ km, and will fall off by only 10 - 20 % in Ω_{GW} (5 - 10 % in amplitude) for the Edwards-Columbia separation. Thus, we do not advocate constraining the distance D between sites on the basis of sensitivity to stochastic background.

Since our primary goal of discovering waves is not significantly affected by site separation, we are free to adjust the separation so as to optimize the information gained from the waves. The primary influence of separation is on the angular resolution obtainable from the time delay between the sites: When the detectors have optimal relative orientations (as we recommend), one can determine $\Theta \equiv$("opening angle")=(angle between source direction and line connecting detectors) to an accuracy

$$\Delta\Theta \simeq \frac{c}{\pi f D \sin\Theta} \frac{1}{\sigma} \simeq \frac{0.5\mathrm{deg}}{\sin\Theta} \left(\frac{1000\mathrm{Hz}}{f} \right) \left(\frac{4000\mathrm{km}}{D} \right) \left(\frac{3}{\sigma} \right) . \tag{4}$$

Here σ is the amplitude signal-to-noise ratio. If the waves are not linearly polarized, this improvement with D will be limited by effects of the earth's curvature (no further improvement, but no debilitation) at $D \times \sigma \sim 12{,}000$km (i.e. $\Delta\Theta$ is limited by Eq. (4) evaluated for $D \times \sigma \sim 12{,}000$km). This limitation is due to the fact that, even with optimal relative orientation of the detectors, the two detectors will be in different planes and thus will measure different polarization states of the waves and thence will see different wave forms. For burst sources, in order to be sure that a given event is real and is not just Gaussian noise, one must have $\sigma \gtrsim 5$; and most sources observed will be near the lower limit of 5. Correspondingly, for burst sources whose polarization is not linear, the distance beyond which further improvement in angular resolution ceases is $D_{\mathrm{max}} \simeq 12000/5 \simeq 2500$ km. On the other hand, for linear polarization or if other detectors in the world-wide net help provide details of both wave forms, the improvement in angular resolution with increasing D will continue beyond $D_{\mathrm{max}} \simeq 2500$ km.

Taking all the above considerations into account, for optimization of gravity-wave discovery via reduction of correlated noise at the two sites we recommend a site separation D in excess of ~300km (a flaky limit that deserves greater study if it becomes an important issue); and in order to optimize the information gained from the waves we recommend D in the range 2500 km to 4500 km.

4. Direction between the sites

So far as we can see, the direction between the sites (easterly, northerly, ...) has no significant impact on the probability of discovering gravitational waves. However, direction can affect the accuracy of position determination by a network of detectors. Since it seems fairly likely that the Europeans will have one or more detectors working simultaneously with the LIGO and conceivable that the Japanese will, it would be desirable to choose a direction between the American sites which, combined with that between America and Europe (and possibly between America and Japan), gives optimal time-delay-determined angular resolution.

From the time delays for three sites one can constrain the position of a source to lie within one of two error boxes. The error boxes are centered on the actual direction $\vec{n}$=(unit vector) to the source and the reflection $\vec{n}'$ of that direction in the plane formed by the site-to-site baselines; and they have areas (in steradians)

$$\Delta\Omega = \frac{4c^2\tau_a\tau_b}{|(\vec{a}\times\vec{b})\cdot\vec{n}|}\ , \qquad (5)$$

where $\vec{a}$ and $\vec{b}$ are the vector separations of sites 2 and 3 from site 1, and the accuracy with which the time delays Δt_a and Δt_b along these separations can be measured is $\pm\tau_a$ and $\pm\tau_b$. From the discussion of timing accuracy in the previous section one can infer that (i) for linearly polarized waves, or for elliptic polarization with an adequate network of detectors to determine both wave forms, the timing accuracies τ_a and τ_b will be independent of site separations $|\vec{a}|$ and $|\vec{b}|$; and (ii) for elliptically polarized waves with little information about one of the wave forms, τ_a and τ_b will be independent of $|\vec{a}|$ and $|\vec{b}|$ out to distances $|\vec{a}|$~2500 km and $|\vec{b}|$~2500 km, and thereafter will increase linearly with distance. Little or nothing is lost in case (ii) if we optimize for case (i); and in this case the size of the error box on the sky [Eq. (5)] is inversely proportional to the following "Area Factor"

$$A_M \equiv \frac{|\vec{a}\times\vec{b}|}{R_\oplus{}^2}\ , \qquad (6)$$

where $R_\oplus$ is the radius of the earth. For several interesting triplets of sites (to be discussed in Sec. II below) this Area Factor has these values:

Sites	A_M
Edwards-Columbia-France	0.43
Edwards-INEL-France	0.15
Edwards-LSU-France	0.44
Columbia-INEL-France	0.37
Columbia-LSU-France	0.18
INEL-LSU-France	0.43

Edwards-Columbia-Japan	0.85
Edwards-INEL-Japan	0.21
Edwards-LSU-Japan	0.44
Columbia-INEL-Japan	0.66
Columbia-LSU-Japan	0.60
INEL-LSU-Japan	0.56

Here France has been chosen as a geometric mean of Britain, France, and Germany; INEL is the Idaho National Engineering Laboratory near Idaho Falls, Idaho; and LSU is Louisiana State University in Baton Rouge; see Sec. II below. Since $\Delta\Omega \propto A_M^{-1}$, the larger the Area Factor is, the better. These Area Factors suggest that one might think of LSU as a reasonable alternative to Columbia, and INEL as a reasonable alternative to Edwards; but INEL is a poor alternative to Columbia, since Edwards-INEL-France gives a poor Area Factor. We shall return to specific site comparisons in Sec. II below.

It is conceivable that, at the time the first two LIGO sites are operating, both the Europeans and the Japanese will also have operating detectors, and conceivable that Perth will switch from bars to interferometers (or that the Perth bar will give useful data) producing a Perth-America-Europe combination. If so, to get optimal time-delay-based position measurements for sources at all locations on the sky, and to optimally distinguish between a source direction $\vec{n}$ and its reflection $\vec{n}'$ in a 3-site plane, we should have the maximum possible value for the "Volume Factor"

$$V_M = \frac{|\vec{a} \times \vec{b} \cdot \vec{c}|}{R_\oplus^2} . \qquad (7)$$

Here $\vec{a}$, $\vec{b}$, and $\vec{c}$ are the vector separations of sites 2, 3, and 4 from site 2. Values of this Volume Factor for various site combinations are:

Sites	V_M
Edwards-Columbia-Europe-Japan	0.07
Edwards-INEL-Europe-Japan	0.14
Edwards-LSU-Europe-Japan	0.16
Columbia-INEL-Europe-Japan	0.05
Columbia-LSU-Europe-Japan	0.19
INEL-LSU-Europe-Japan	0.21
Edwards-Columbia-Europe-Perth	0.34
Edwards-INEL-Europe-Perth	0.11
Edwards-LSU-Europe-Perth	0.60
Columbia-LSU-Europe-Perth	0.09
Columbia-INEL-Europe-Perth	0.35
INEL-LSU-Europe-Perth	0.09

Note that with Europe and Japan, particularly good site pairs are INEL-LSU, Columbia-LSU Edwards-LSU, and Edwards-INEL; while with Europe and Perth, particularly good are Edwards-LSU, Columbia-INEL, and Edwards-Columbia.

In view of the ranges of values of A_M that are achievable, we recommend that the first two LIGO sites, together with Europe, be able to achieve $A_M \gtrsim 0.35$. We also suggest a preference for large Volume Factors with Europe and Japan or with Europe and Perth, though in view of the enormous uncertainty whether Japan or Perth will build full-scale interferometric detectors within a reasonable time frame, we regard this as a weak preference.

5. Latitude of the sites

The Virgo cluster of galaxies is the closest concentration of matter at a distance large enough that the number of sources per unit volume approaches a constant. It is located near the celestial equator, and therefore sites which have the celestial equator near the zenith (sites near the earth's equator) will have better sensitivity to Virgo's gravity waves than sites further north. Schutz and Tinto (1987, Figs. 8, 9, 10) have computed for a source in Virgo the signal-to-noise ratio $\sigma_{\rm rms}$ (square root of the quantity they plot), rms averaged over source polarization and time of day, as a function of detector latitude; and we have computed the signal-to-noise ratio $\sigma_{\rm opt}$ for optimal polarization and optimal time of day. Both quantities vary with absolute orientation of the detector only by amounts $\lesssim$5 per cent, and both vary with latitude over the United States as follows:

Site	**Latitude**	σ/σ_{LSU}
LSU	30.5 degrees	1.00
Edwards	35 degrees	0.96
INEL	43 degrees	0.90
Columbia	45 degrees	0.89

Thus, the preference for the more southerly sites is at the 10 per cent level which some of us regard as significant, but just barely so – and that preference relies on the rather uncertain assumption that the first sources to be detected will be in the Virgo cluster.

As a generalization of these Virgo considerations, more northerly detectors tend to get more intense coverage of a smaller region of the sky, that near the poles; while detectors nearer the equator get less intense coverage of a larger region of the sky, that near the celestial equator. It is not at all obvious to us which is preferable. Moreover, the effect is not great: The the solid angles of sky, $\Delta\Omega_{1/2}$ swept out by the antenna beam patterns [zenith angles $\theta<\theta_{1/2}\cong35$ degrees and $(180\,\text{degrees}-\theta)<\theta_{1/2}$] for detectors at different latitudes are

Site	$\Delta\Omega_{1/2}/4\pi$
LSU	0.91
Edwards	0.94
INEL	0.85
Columbia	0.81

Detailed maps of the sky coverage of several pairs of sites in the U.S. are presented in Appendix I. The most important feature of those maps, from the viewpoint of site selection, is that they are so similar from one pair of sites to another: they do not suggest a strong preference for any pair or a strong rejection of any.

In summary, we do not regard the latitudes of the sites as a major issue, though detection of the Virgo cluster suggests some preference for more southerly sites.

6. Opening angle of detectors

Throughout the above discussion we have assumed, tacitly, that the L at each of the initial sites will have an opening angle of 90 degrees. If we were to plan for a German-type triangular system in a future upgrade at either site, we should begin with an opening angle of 60 degrees. As we shall discuss in detail in Sec. I.C.6 below, we believe that the 13% penalty in sensitivity that would result from an initial opening angle of 60 degrees is not justified by the savings to be made in a possible future upgrade; and correspondingly we recommend initial opening angles of 90 degrees at both sites.

C. Future Upgrades

1. Goals

To the extent that it does not compromise the probability of initial discovery of gravity waves, the initial sites should be chosen so as to optimize the possibilities for future upgrades. The upgrades would be aimed at improving significantly the detector sensitivities and/or increasing the amount of information extracted from each wave.

The attractiveness of various upgrades will depend very much on the status of detectors elsewhere in the world at the time of upgrade; and since that cannot be predicted, we should be prepared for a number of different possibilities. As an aid to sorting out these possibilities, we examine qualitatively in Appendix E the information that can be extracted with various numbers of detector-containing vacuum systems (henceforth called "L's") at various numbers of sites; and in Appendix F we make quantitative comparisons between two possible upgraded configurations (see below for discussion). Here in the body of the report we discuss each possible upgrade with emphasis on two aspects: the likelihood that we will face a situation where we will want to make that upgrade, and the influence of our initial choice of sites on that upgrade.

2. Increase in arm length

The sole motivation for an increase in arm length beyond 4 km would be to produce an increase in sensitivity. We might seek an arm length increase if 4 km detectors fail to discover waves; but our probability of getting the funds in that case seems so low that the committee believes we should not let it influence our choice of sites. Once waves have been discovered, then we would think it more attractive to upgrade in the direction of extracting full information from the waves than to increase the arm length (see below). Only after there exists an adequate worldwide network for full information extraction is an arm-length increase likely to seem attractive (and it then would be most attractive for sources in the frequency band where the signal-to-noise ratio σ scales linearly with length). However, since that time may eventually come, we might wish to consider arm-length expansion in our choice of sites.

Why might one increase the arm length rather than just build more L's? (i) Adding a second L of length equal to the first increases the joint signal-to-noise ratio σ by a factor $\sqrt{2}$, whereas if the noise sources hanging us up were to scale down linearly with length, doubling the length would increase σ by a factor 2. (ii) On a sufficiently flat site, the cost of doubling the arm length will be less than that of building a new L with length equal to the first.

If we one day choose to increase the arm length, only a very substantial increase (say, a factor 2 to 10) is likely to be justifiable. Correspondingly, sites that can accommodate future-expansion arm lengths of at least 8 km are to be preferred over smaller sites, other things being equal; but there is little preference for a site expandable to, say, 6 km over one restricted to 4. Note, however, that there are very few sites which could handle even 8 km, much less 40 km: It is our impression (we have *not* checked it) that among those discussed above (Edwards, Columbia, INEL, LSU) only INEL could handle 8 km; and among all the sites in the huge table in Appendix H, only the Great Salt Lake Desert (Utah) can accommodate 40 km.

In view of the fact that we are more likely to want to upgrade by adding a 3rd site and/or a 45-degree rotated L at an original site than by lengthening the arms, and in view of the paucity of huge sites, with or without existing infrastructure, we do not view arm length expandability as a major consideration in site selection.

3. Addition of one L at only one of the original sites

Appendices E and F suggest (but it is not yet firmly proved) that the most accurate way to get both wave forms $h_+(t)$ and $h_\times(t)$ is to: (i) construct two L's at the same site, oriented 45 degrees to each other, (ii) with those L's measure the two time series $\Delta L_1(t)/L_1$ and $\Delta L_2(t)/L_2$, (iii) combine those time series with a source position obtained with the help of other L's at two or more other sites, and (iv) from that combination extract $h_+(t)$ and $h_\times(t)$. Correspondingly, we believe that, if the Europeans and/or Japanese have provided the world-wide network with one or more additional baselines with which to get direction information, our first upgrade would be to add a second L at one of our original sites. Thus, at least one of our original sites should be capable of accommodating a second L, rotated 45 degrees to the first.

Note: A careful error analysis may reveal that a good solution for both wave forms can be obtained with any network of single L's which is sufficient to give unambiguous positions. If that proves to be the case, then there might not be any need to add a 45-degree L even at one site. However, since the capability exists at Edwards (and at LSU and INEL), the LIGO project will be prepared for either case.

4. Addition of one new L at each of the original sites

There are two circumstances under which one might have thought it desirable to add a new L, rotated by 45 degrees to the first, at both of the original sites:

(1) One might have thought this a good way to enhance one's sensitivity to both wave forms, $h_+(t)$ and $h_\times(t)$. Not so, we believe: Better ways are these: (a) If a third site is being built to help with position resolution (see above), it would be best to build its L rotated 45-degrees to the original two, and add one 45-degree-rotated L at just one of the original sites. (b) If a third site is not being built and if noise sources are scaling down linearly in length (or as the square root of length), it would be cheapest to build a $4\times\sqrt{2}=5.7$ km (or, if the site will permit, a $4\times2=8$ km) rotated L at

one of the original sites rather than a rotated 4 km L at the both of the original sites. Of course, the one longer L would produce less discrimination against non-Gaussian noise than the two 4 km L's. However, we think it very likely that for most sources there will be sufficient signal in the first pair plus the rest of the world's detectors to produce adequate non-Gaussian discrimination.

(2) One might have thought that, if the rest of the world has not produced detectors, an attractive way "on the cheap" to acquire sensitivity to both $h_+(t)$ and $h_\times(t)$ and simultaneously get reasonable directional information about a source's direction θ,ϕ, would be (a) by building the original sites far enough apart (say, Columbia and Edwards) that the angle between their planes is reasonably large ($\beta \sim 38$ degrees), (b) by upgrading with the addition of new, 45-degree rotated L's at both sites, and (c) by trying to extract from the four Ls' outputs the four quantities h_+, $h_\times$, θ, and ϕ. In fact, this is possible in principle. However, detailed calculations described in Appendix F show that this "2-site, 4-L" method of getting the information is significantly inferior to the "3-site, 4-L" method advocated in part (a) of the last paragraph — inferior in two ways: (i) it is a much less robust method (see Appendix F for a detailed discussion of the difficulties); (ii) even under the best of circumstances it is rather less accurate: discarding all cases where the ratio of the weakest of the four signal strengths to the strongest is less than 1/5, the two methods have the following average accuracies:

$$\Delta\Omega \sim 520\mathrm{deg}^2 \times \left[\frac{\delta SSR}{0.3}\right]\left[\frac{\delta\tau_{1,2}}{0.3\mathrm{ms}}\right] ,$$

$$\Delta\Omega\Delta\psi \sim 2350\mathrm{deg}^3 \times \left[\frac{\delta SSR}{0.3}\right]^2\left[\frac{\delta\tau_{1,2}}{0.3\mathrm{ms}}\right] \text{ for 2 sites, 4 L's ;} \tag{8a}$$

$$\Delta\Omega \sim 53\mathrm{deg}^3 \times \left[\frac{\delta\tau_{1,2}}{0.3\mathrm{ms}}\right]^2 ,$$

$$\Delta\Omega\Delta\psi \sim 540\mathrm{deg}^3 \times \left[\frac{\delta SSR}{0.3}\right]\left[\frac{\delta\tau_{1,2}}{0.3\mathrm{ms}}\right]^2 \text{ for 3 sites, 4 L's .} \tag{8b}$$

Here $\Delta\Omega$ is the size of the error box on the sky, $\Delta\psi$ is the uncertainty in the instantaneous polarization angle, $\delta\tau_{1,2}$ is the accuracy with which the time delay between the two sites can be determined from the observed time series, δSSR is the accuracy with which the amplitude signal strength ratio can be determined for the four L's, and the numbers correspond to Edwards and LSU as the two sites which each have two L's; and Edwards with 2, Columbia and LSU with 1 in the 3-site method.

In summary, we think it very unlikely that a desirable upgrade will entail new L's at both original sites; and correspondingly, we do not recommend constraining both sites to accommodate 45-degree rotated L's.

5. Addition of new sites

If the world-wide net, at the time of upgrade, is not capable of giving full directional information (i.e. does not have three baselines with a reasonably large Volume Factor V_M), then — in accord with the above discussion and with Appendices E and F — we think it likely that we will want to build a third site in the United States to enhance direction determination. A fourth site would be attractive only if it were added outside the contiguous United States, since those states lie so nearly in a plane that they cannot produce by themselves a large V_M.

Accordingly, we recommend that our first two sites be so chosen as to be able, by the addition of a third American site, to produce a large Area Factor, $A_M \gtrsim 0.12$. Our recommended limit of 0.12 is based solely on the following range of values that is readily achievable:

Sites	A_M
Edwards-Columbia-LSU	0.14
Edwards-INEL-LSU	0.06
Columbia-INEL-LSU	0.15

Note that, if these four sites were our only options, it would be unwise as an initial pair of sites to choose Edwards-INEL — a combination that we had already ruled out on the basis of a poor Area Factor with Europe. However, all other pairs would be acceptable.

6. The German Triangular Configuration

The upgraded configuration of two L's at one of the original sites can be accomplished by either of two methods: (i) By two L-shaped (90-degree) vacuum systems,. rotated 45-degrees with respect to each other (the method described above), or (ii) by a single equilateral triangular vacuum system in which three antennas are operated simultaneously, one with its corner station at each vertex (the method proposed by the German group). The choice of method places constraints on the shape of the original site — and the choice affects also the geometry of the first, pre-upgrade L.

We strongly recommend pursuing the two-90-degree-L configuration rather than the triangular configuration. Our reasons are these: (For justification of many of the statements made here see Appendix G.)

The initial, pre-upgrade configurations in the two cases are single L's with opening angles α=90degrees and α=60degrees. Other things (arm lengths, optics, etc.) being equal, the signal-to-noise ratios in the two L's are proportional to sinα, and thus $\sigma_{60}/\sigma_{90}=0.87$ — a debilitation somewhat outside the 10 per cent tolerance that we believe is acceptable (cf. Appendix A). If we are not willing to live with this debilitation of signal-to-noise but still want to prepare for a triangular configuration, then we must give the 60-degree L arm lengths of (i) $4/.87=4.6$ km at an increased cost of roughly 4 million dollars, if σ scales linearly in $1/L$, or (ii) $4/(.87)^2=5.3$ km at an increased cost of roughly 8 million dollars, if σ scales as the square root of $1/L$. *The financial compensation for this added up-front cost would come only at the time of upgrade — presumably after gravity waves are discovered, when money is easier to obtain than now.* An extremely rough estimate (see end of Appendix G for details) suggests that that saving might be 13 million uninflated dollars — 1.6 to 3.2 times the upfront cost.

We do not think that this 16 million dollar saving in an upgrade that we might or might not want to make someday is sufficient, in the American context, to justify the penalty of 4-to-8 million dollars or 13% sensitivity loss in the initial configuration. (In the German context, where politics are different and where the cost structure is different because the entire L must be buried, the optimal decision might be different.)

II. Implications for Specific Sites

A. Edwards-Columbia

The primary pair of sites currently under consideration is Edwards Air Force Base, California and Columbia, Maine. This preliminary choice of sites was reached after an extensive search of the entire continental United States. See Appendix H for a list of the sites considered and references to the search reports.

The Edwards/Columbia choice of sites is not precluded by any of the scientific arguments discussed above. It is possible to construct a 90 degree detector at each site, and it is possible to adjust the Edwards L into coincident projection with that of Columbia. The baseline is desirably long, and the direction of the baseline, in conjunction with that to a with a third site in Europe or Japan or in the United States, is good for determining source positions by time delay (it has a large Area Factor A_M). However, its Volume Factor with Europe and Japan is not favorable — a modest, but in our view not major, detriment, somewhat compensated by a good Volume Factor with Europe and Perth. Edwards has 4% worse sensitivity to the Virgo cluster than the best sites in the contiguous United States, while Columbia is 11% worse than the best sites — again in our view a modest, but not major detriment.

Expansion of the Columbia site to include another, 45-degree rotated L is not practical because of the local terrain. However, Edwards is expandable; and, as was argued above, it is unlikely that we will want to add a second detector at both sites.

Edwards Air Force Base has much of the infrastructure needed to support a gravitational wave detector on site. The site at Columbia does not have much existing infrastructure, though people at the University of Maine at Orono have expressed interest in joining the project and the State of Maine has indicated informally a willingness to contribute money and resources to keep the costs of construction competitive.

B. INEL, Idaho

The proposed site at the Idaho National Engineering Laboratory is very flexible for both antenna orientation and future expansion. In the past INEL has been regarded as an alternative to Columbia. This, we now claim, was a mistake: the Europe-INEL-Edwards Area Factor A_M is so poor that these sites would give inadequate accuracy for source positions. Instead, INEL should be regarded as an alternative to Edwards (and LSU, discussed below, an alternative to Columbia); see the A_M's of Sec. I.B.4 above.

C. LSU

A site on the campus at Louisiana State University has recently been suggested as a good place for one of the initial LIGO sites. This site is currently part of an agricultural test facility and is quite flat. Proponents (Joe Reynolds, a dean at LSU and former member of the NSB, and and Warren Johnson, a gravity experimenter at LSU) report that the site is seismically quiet and there is an existing and eager infrastructure.

The baseline with Edwards is adequately large, about 2600 km, and is oriented so that the Edwards-LSU-Europe Area Factor and the Edwards-LSU-Europe-(Japan or Perth) Volume Factors are large and would thus give good directional accuracy. Therefore, we regard LSU as a possible alternative to Columbia. LSU is about as far south as one can get in the contiguous United States and thus gives maximal sensitivity for the Virgo cluster — a modest, but not major consideration.

Since the LSU site was suggested so recently, it has not been thoroughly examined. There is some indication on available maps that the area suggested contains marshland. However, since there is nothing firm to preclude the site and it looks attractive (though not substantially more so than Columbia) from a scientific viewpoint, a closer look may be in order.

E. Other Sites

We have tried to present our scientific considerations (Sec. I) and our recommendations (Sec. III) in such a way that they can readily be applied to other sites in the continental United States. Our choosing to focus, above, on LSU and INEL (in addition to Edwards and Columbia), rather than on other sites, was somewhat arbitrary.

III. Summary of Recommendations.

We summarize here the various conclusions and recommendations made in Secs. I and II:

1. In terms of our scientific criteria for site selection, the preliminarily chosen site pair, Edwards/Columbia, is perfectly acceptable. Also acceptable would be the INEL/Columbia pair, and the Edwards/LSU pair.
2. The fundamental scientific criteria for site selection are, *first*, that the initial LIGO configuration, including sites, be one which comes close to optimizing the probability of successfully discovering gravitational waves; and *second* that, to the extent the configuration can be adjusted to optimize the information extracted from the waves — both before and after upgrades — without much compromising the probability of discovery, it should be so adjusted. In our view these fundamental criteria have the following implementations:
3. The relative orientations of the detectors at the two sites should be optimized (same projections of leg directions onto the plane bisecting the two detectors' planes, to within an error box of width ±13 degrees centered on the average of coincident projection and Virgo-optimized projection). The absolute orientation within this constraint is not important.
4. The site separation should exceed ~300 km (a very flaky number) in

order to assure uncorrelated noise at the two sites; and there is a modest preference for the range 2500 km to 4500 km in order to maximize directional accuracy.

5. The site separations and the directions between sites should be such as to give values of A_M [Eq. (6)] in the range $A_M \gtrsim 0.35$ for the triplet of sites Europe - [LIGO site 1] - [LIGO site 2]; and there should exist a third American site for a potential upgrade of the system which would give an A_M for [LIGO site 1] - [LIGO site 2] - [LIGO site 3] in the range $A_M \gtrsim 0.12$. A large Volume Factor V_M for [LIGO site 1] - [LIGO site 2] - Europe - Japan or [LIGO site 1] - [LIGO site 2] - Europe - Perth would be desirable, but is not terribly important.
6. The latitudes of the sites are not a major issue, though detection of the Virgo cluster suggests some preference for more southerly sites.
7. Sites that can accommodate future-expansion arm lengths of at least 8 km are to be preferred over smaller sites, other things being equal; but this is not a major consideration.
8. One of the original sites, but not necessarily both, should be capable of accommodating a second 4 km L, rotated 45-degrees relative to the first.
9. At both sites the initial vacuum systems should be right-angle L's, rather than 60-degree L's as would be required to prepare for a German-triangle upgrade.

References

Schutz, B. F. and Tinto, M. 1987, Monthly Notices of the Royal Astronomical Society, **224**, 131.

Tinto, M. 1987a, Monthly Notices of the Royal Astronomical Society, **226**, 829.

Tinto, M. 1987b, unpublished PhD thesis, University College, Cardiff, Wales; copies are available from Site Working Group members.

Whitcomb, S. 1984, internal LIGO Project memorandum, reproduced in Appendix B of this Report. are

Appendix A
The Acceptable Sensitivity Penalty for Improved Information Extracted from the Waves, or Improved Upgrade Possibilities

In designing the initial LIGO configuration, including site selection, there should be some upper limit on the fractional decrease, $\Delta\sigma/\sigma$, of amplitude signal-to-noise ratio that is an acceptable price to pay for significant increases in the information extracted from the waves, or for significant improvements in the possibilities of future LIGO upgrades. In the body of this report we propose the upper limit

$$\frac{\Delta\sigma}{\sigma} \leq 0.1 \ . \tag{A.1}$$

In this appendix we will explain why some members of this committee would be unhappy with an upper limit in excess of 0.1, by describing some implications of various values of the limit. More specifically: we shall suppose, throughout this appendix, that some design choice (such as non-coincident-projection alignment of the L's at the two LIGO sites, or a non-90-degree opening angle for one or both L's) has produced a reduction in the signal-to-noise ratio, for all sources, by a fractional amount $\Delta\sigma/\sigma$ (defined as positive for a reduction); and we ask what the consequences of that reduction are.

We must emphasize from the outset that the reduction $\Delta\sigma/\sigma$ can never be regained without a complete rebuilding of the vacuum system, at enormous expense. (One might think that so small a reduction as $\Delta\sigma/\sigma=0.1$, say, can readily be compensated for by a modest improvement in optics and/or laser power. However, the optics or laser improvement is possible whether or not the debilitating feature was built into the LIGO design; and thus, after the improvement, one still has a signal-to-noise ratio 10 per cent lower than one would have had without the debilitating feature).

1. Increase in the mean time between gravity-wave bursts

Since it is likely that the burst sources detectable with the LIGO will come from at or beyond the Virgo cluster of galaxies, where the spatial density of sources is uniform, the mean time between arrivals of bursts with gravity-wave amplitudes larger than some value h will likely scale as $\Delta\tau \propto h^{-3}$. Correspondingly, the design-imposed reduction in all signal-to-noise ratios will produce the following increase in the mean time between detectable bursts:

$$\left(\frac{\Delta\tau}{\tau}\right)_{\text{burst}} = \frac{1}{(1-\Delta\sigma/\sigma)^3} - 1 = 0.37 \text{ if } \Delta\sigma/\sigma=0.1 \ . \tag{A.1}$$

This 37% increase in mean time between detections will be with us until, at very great expense, there is a major reconstruction of the LIGO facility.

2. Increase in the integration time to discover or measure a periodic source

Regardless of where it is located, a periodic source will produce a signal-to-noise ratio in the LIGO detectors that grows as the square root of the integration time. Correspondingly, the design-imposed reduction in all signal-to-noise ratios will impose the following increase in the integration time to detect or measure any periodic source:

$$\left(\frac{\Delta\hat{\tau}}{\hat{\tau}}\right)_{\text{periodic}} = \frac{1}{(1-\Delta\sigma/\sigma)^2} - 1 = 0.23 \text{ if } \Delta\sigma/\sigma = 0.1 \ . \tag{A.2}$$

3. Increase in the integration time to discover or measure stochastic background

The amplitude signal-to-noise ratio in a stochastic-background search grows as the fourth root of integration time. Correspondingly, our $\Delta\sigma/\sigma$ will produce the following increase in the integration time to discover or measure a stochastic background:

$$\left(\frac{\Delta\hat{\tau}}{\hat{\tau}}\right)_{\text{stochastic}} = \frac{1}{(1-\Delta\sigma/\sigma)^4} - 1 = 0.52 \text{ if } \Delta\sigma/\sigma = 0.1 \ . \tag{A.3}$$

4. Increase in probability that the LIGO project will be shut down for failure to discover gravitational waves

Once the LIGO is in operation, we can expect the sensitivities of the detectors in it to improve fairly steadily (though, of course, in discrete steps) for some years. If we are lucky, at some point during that improvement, gravity waves will be discovered. In this case a 10% debilitation of σ due to LIGO design choices is unimportant: It will delay the discovery of gravity waves by only ~1 to 3 months, since the sensitivity will probably be improving by 3% to 10% per month on average.

If gravity waves are not discovered during this initial epoch of steady sensitivity improvement, it is unlikely we will get the funding for a major upgrade of the LIGO facilities, and as a result the sensitivity improvement will ultimately grind to a halt or a slow crawl (i.e. become "stuck"). If the sensitivity in this stuck epoch is too poor, we will fail, year-after-year to discover gravity waves and ultimately the NSF will shut us down and the field will die. (This presumes, of course, that the Europeans or others are not doing better — a presumption on which our calculations will be based.) The design-imposed signal-to-noise reduction $\Delta\sigma/\sigma$ will reduce the sensitivity at which we get stuck, and thus will increase the probability of our project being shut down. We can estimate that increase in probability of shutdown, $\Delta P_{\text{shutdown}}$, as follows:

Denote by $h \equiv \tilde{h}(f)\sqrt{f}$ the rms detector noise in a bandwidth $\Delta f = f$ at frequency $f = 100$ Hz (where $\tilde{h}(f)$ is the square root of the spectral density of the detectors' strain noise, $\Delta L/L$); and denote by h_{stuck} the noise level at which the detectors become stuck. Further, denote by $h_1 \lesssim h_{\text{stuck}} \lesssim h_2$ the range of dimensionless noise amplitudes in which, based on our best estimates today, the detectors are likely to get stuck, in the absence of a huge infusion of new funds from NSF. For example, a person who feels quite uncertain about whether good sensitivities will ever be achieved in the LIGO might set $h_1 = 3\times10^{-21}$ and $h_2 = 3\times10^{-23}$. It is reasonable to assume that the differential probability dP_{stuck} of getting stuck in a given logarithmic interval $d\ln h$ of h is constant (independent of h) over the range $h_1 < h < h_2$. Finally, denote by $P_{\text{discovery}}(h_1, h_2)$ our best estimate today of the probability that gravity waves will be discovered somewhere (anywhere) in the range $h_1 < h < h_2$. For example, Kip's best estimate for $h_1 = 3\times10^{-21}$ and $h_2 = 3\times10^{-23}$ at $f = 100$ Hz is $P_{\text{discovery}} = 0.7$ (with 20% odds of discovery at $h > 3\times 10^{-21}$ and 10% odds we will have to go to $h < 3\times 10^{-23}$.)

It is straightforward from the above definitions to show that the probability of failure ever to discover gravity waves, and of thus being shut down, is increased, as a result of the design-imposed sensitivity loss $\Delta\sigma/\sigma$, by

$$\begin{aligned} \Delta P_{\text{shutdown}} &= \frac{\Delta\sigma/\sigma}{\ln(h_2/h_1)} \times P_{\text{discovery}}(h_1,h_2) \\ &\simeq 0.02 \ \text{ if } \Delta\sigma/\sigma = 0.1,\ h_2/h_1 = 100, \text{ and } P_{\text{discovery}}(h_1,h_2) = 0.75 \ . \end{aligned} \tag{A.4}$$

Such a 2 per cent increase in probability of shutdown may seem small; but one should remember that shutdown without ever seeing gravity waves would be a very severe and painful capstone to the LIGO Project.

Appendix B
Optimum Alignment of Columbia and Edwards for Linearly Polarized Waves

Stan Whitcomb

January 1985

This Appendix is a reproduction of an internal LIGO memorandum written by Stan Whitcomb in January 1985. It deals with the effects on signal strengths of varying the orientation of the Edwards L, with the Columbia L held fixed at its topography-determined orientation. In the memorandum Columbia is called Cherryfield (its old name). The signal strengths plotted in the figures are $s_j = \sigma_j / \sigma_{\mathrm{opt}}$, where σ_j is the signal-to-noise ratio at site j for a source at its actual location on the sky and actual polarization, and σ_{opt} is the signal-to-noise that the source would have if it were overhead and had optimal polarization. The figures show, for a uniform sampling of source locations and polarizations, the number of sources with various combinations of s_1 and s_2. Each figure corresponds to a specific orientation for the Edwards L. The optimum orientation agrees with coincident projection to good accuracy.

22 JANUARY 1985

DEAR PETER

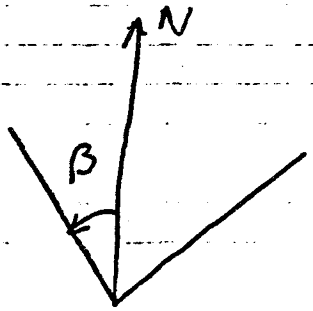
THOUGHT I WOULD SEND ALONG MY LATEST RESULTS ON ORIENTATION. THE CALCULATION IS BASICALLY THE SAME, BUT THE DATA ARE DISPLAYED DIFFERENTLY. FOR THE SAME GRID OF SOURCES (40 θ's x 72 φ's x 18 POLARIZATIONS) I'VE CALCULATED THE SIGNAL STRENGTH IN EACH DETECTOR. THE ATTACHED PLOTS HAVE THE SIGNAL STRENGTHS AS AXES, WITH THE SYMBOLS REPRESENTING THE # OF SOURCES WITH THAT COMBINATION OF SIGNALS

I TRIED TO DO A RUDIMENTARY GRAY SCALE WITH THE PRINTER. EACH PIXEL IS 2 CHARACTERS WIDE, 1 HIGH. THE KEY, IN CASE YOU WANT TO GET QUANTITATIVE, IS

blank	< 5
.	5-14
..	15-24
.:	25-34
::	35-44
:*	45-54
**	55-64
*0	65-74
00	75-84
0X	85-94
XX	≥ 95

THE TWO SCALES (AXES) ARE ALMOST, BUT NOT QUITE THE SAME.

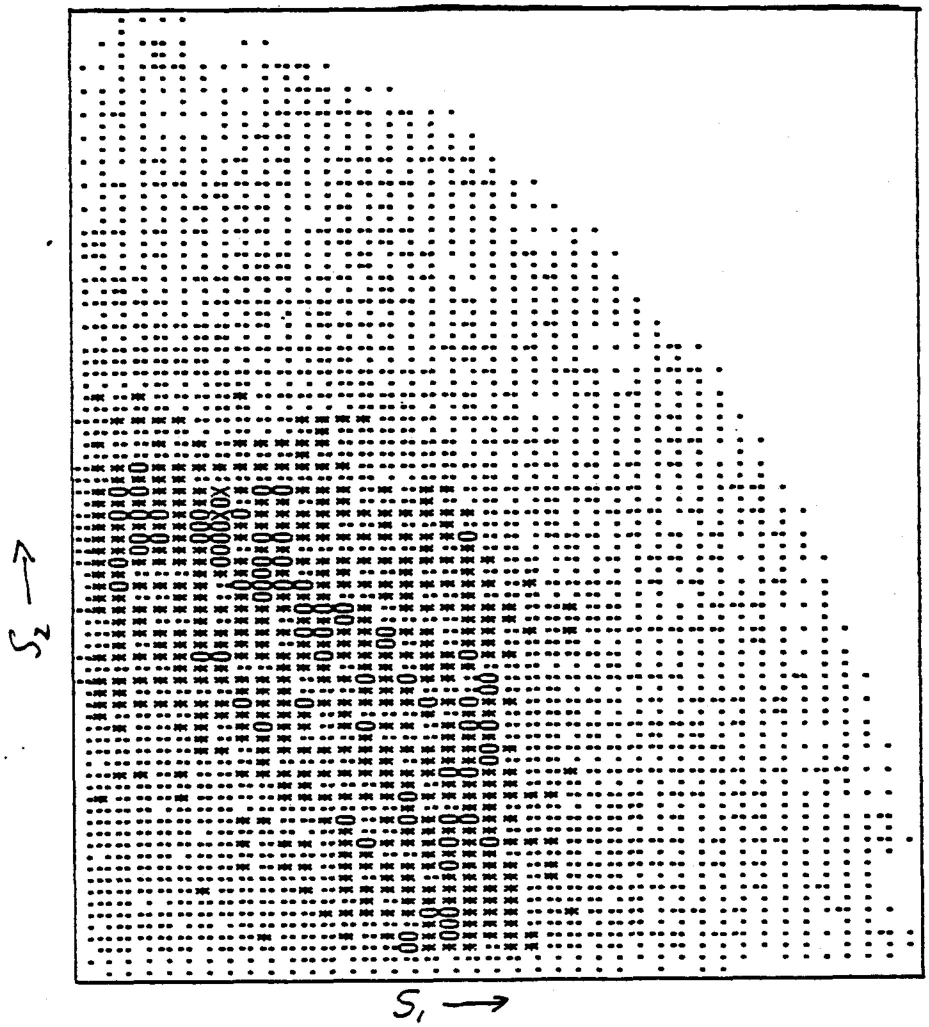
THE SERIES OF PLOTS ARE APPROPRIATE FOR EDWARDS AND CHERRFIELD. THE CF DETECTOR HAS THE REQUIRED ORIENTATION AND THE VARIOUS PLOTS SHOW THE EFFECT OF ROTATING THE EDWARDS DETECTOR. THE ANGLE β IS THE EDWARDS ORIENTATION AS DIAGRAMMED BELOW



OBVIOUSLY, β ~~HAS A 90° AMBIGUITY~~ IS MEASURED MOD 90°. $\beta = 49°$ IS WHAT I WOULD CALL THE NAIVE OPTIMUM. IT MAY ALSO BE THE REAL OPTIMUM.

ED-CF

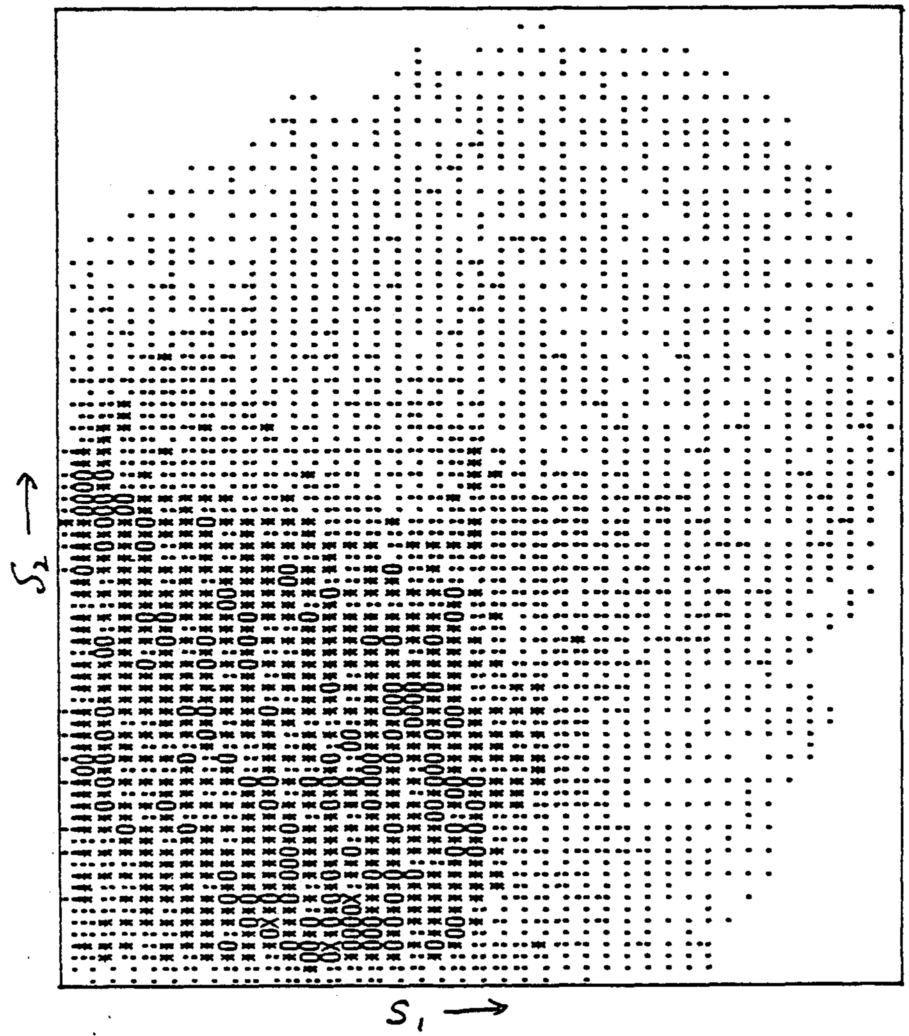
$\beta = 4°$



enter alpha, psi1, psi2

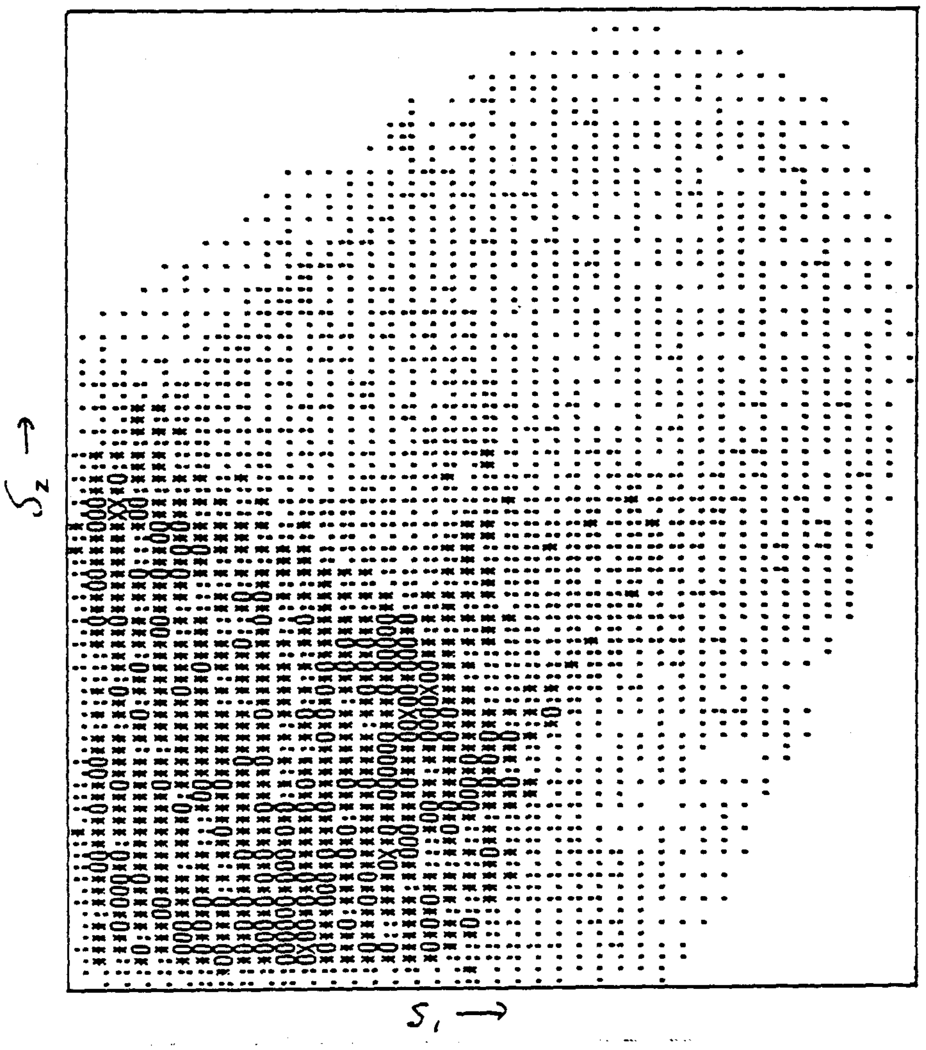
ED-CF

$\beta = 29°$



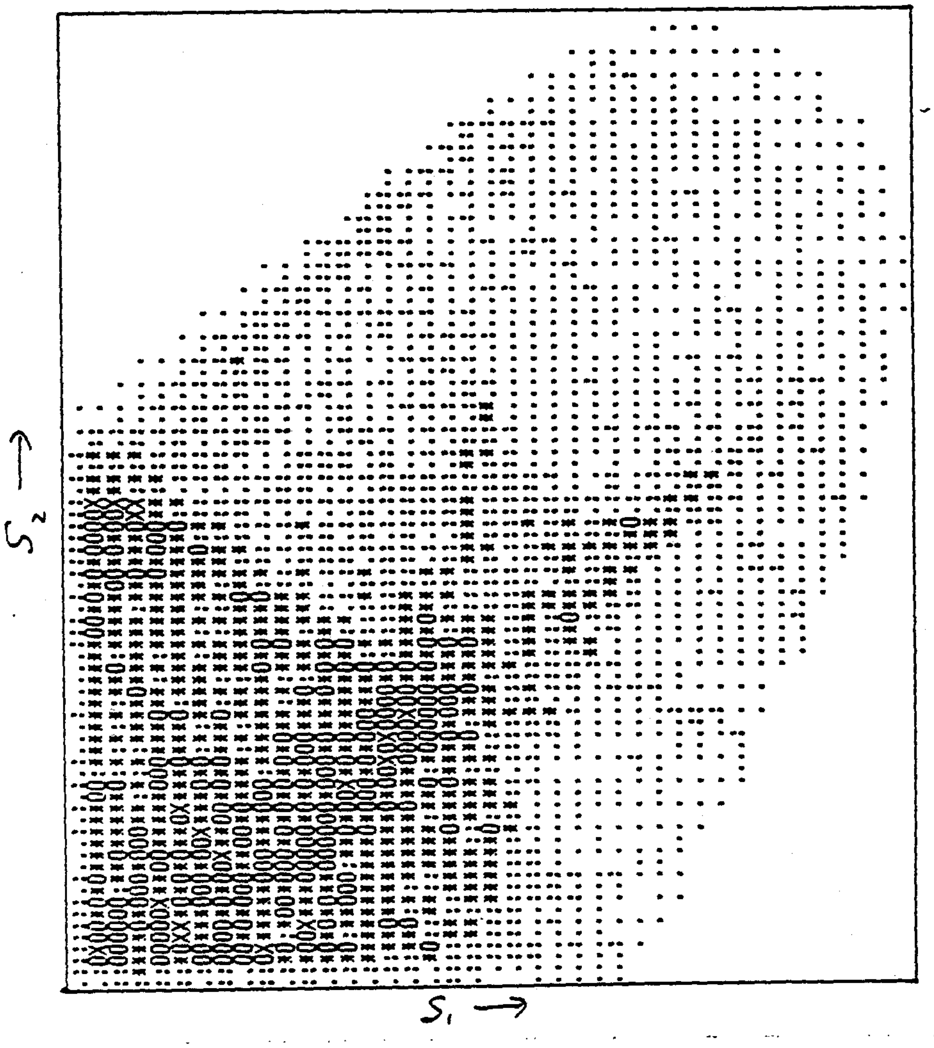
ED-CF

$\beta = 34°$



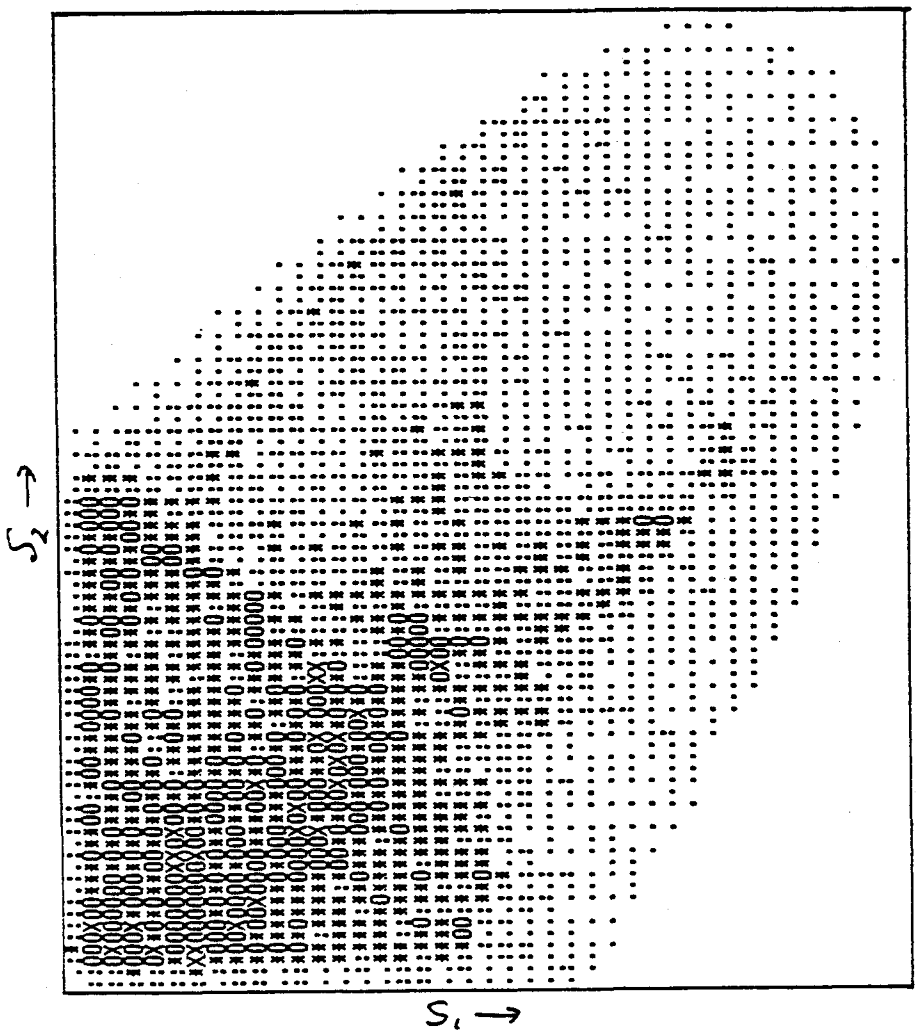
enter alpha, psi1, psi2

ED-CF
$\beta = 39°$



enter alpha, psi1, psi2

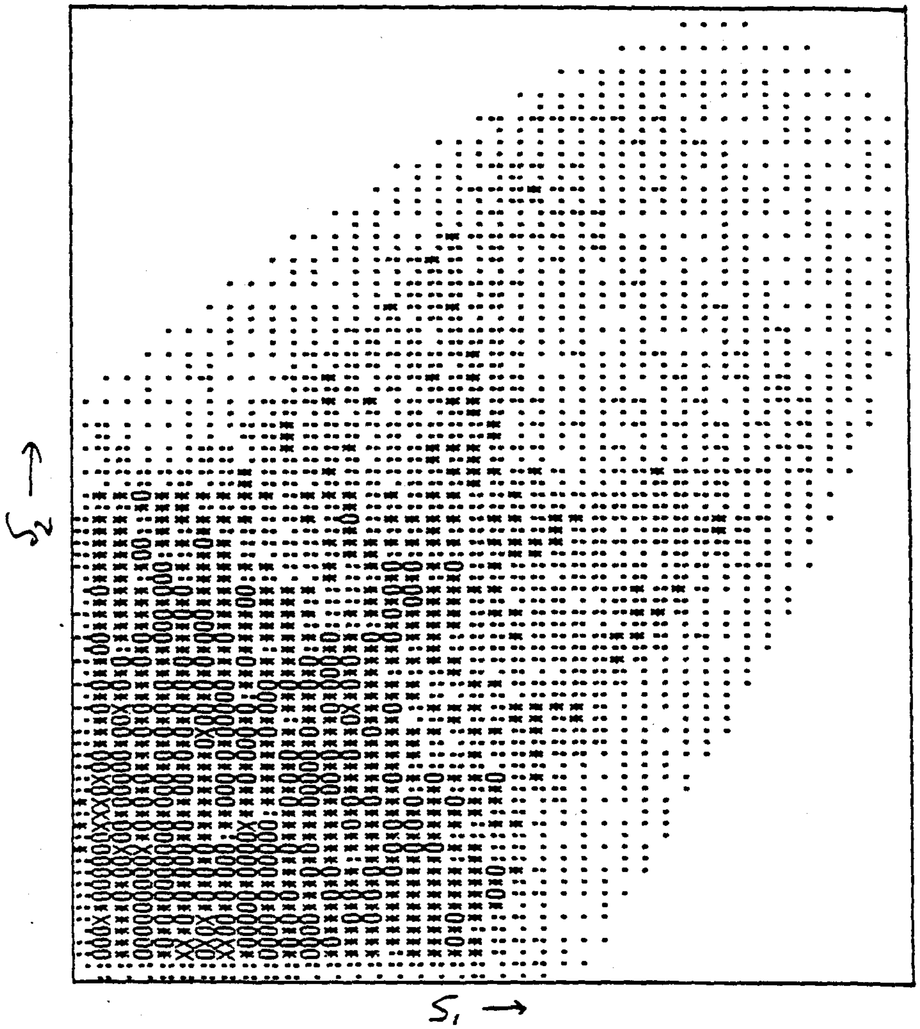
ED- CF
$\beta = 44°$



enter alpha, psi1, psi2

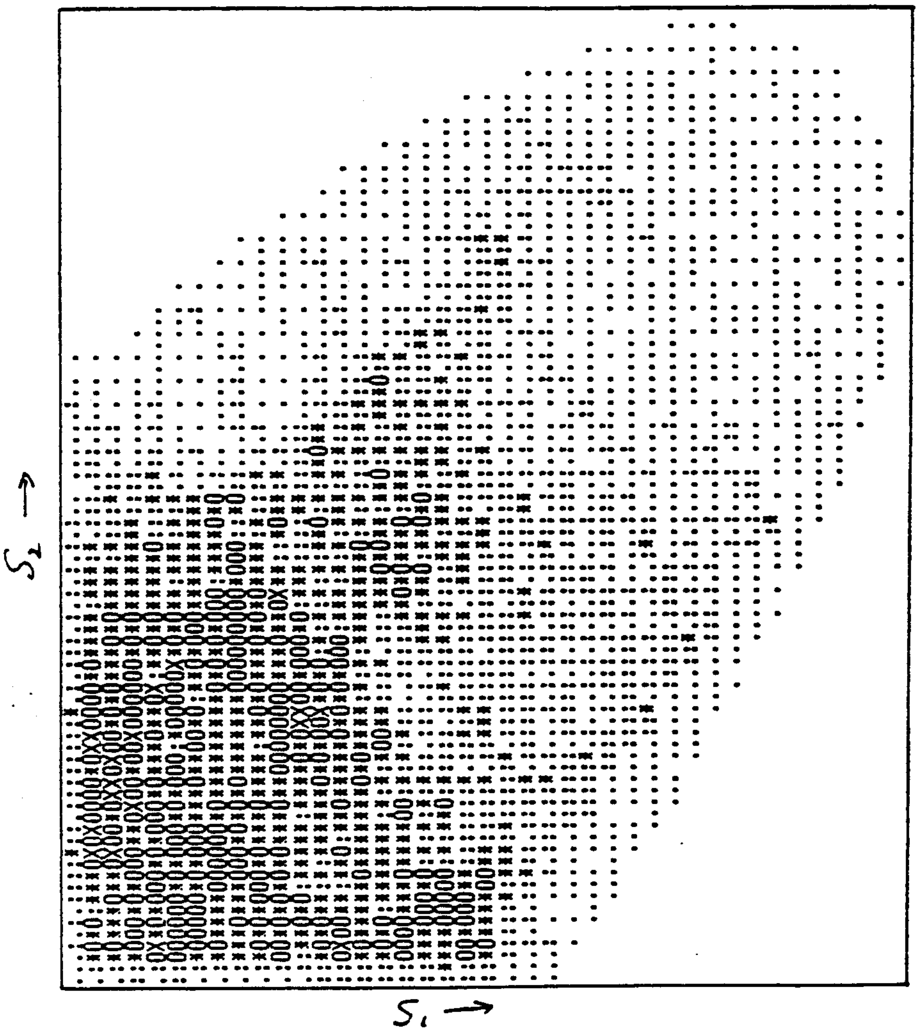
ED-CF

$\beta = 49°$



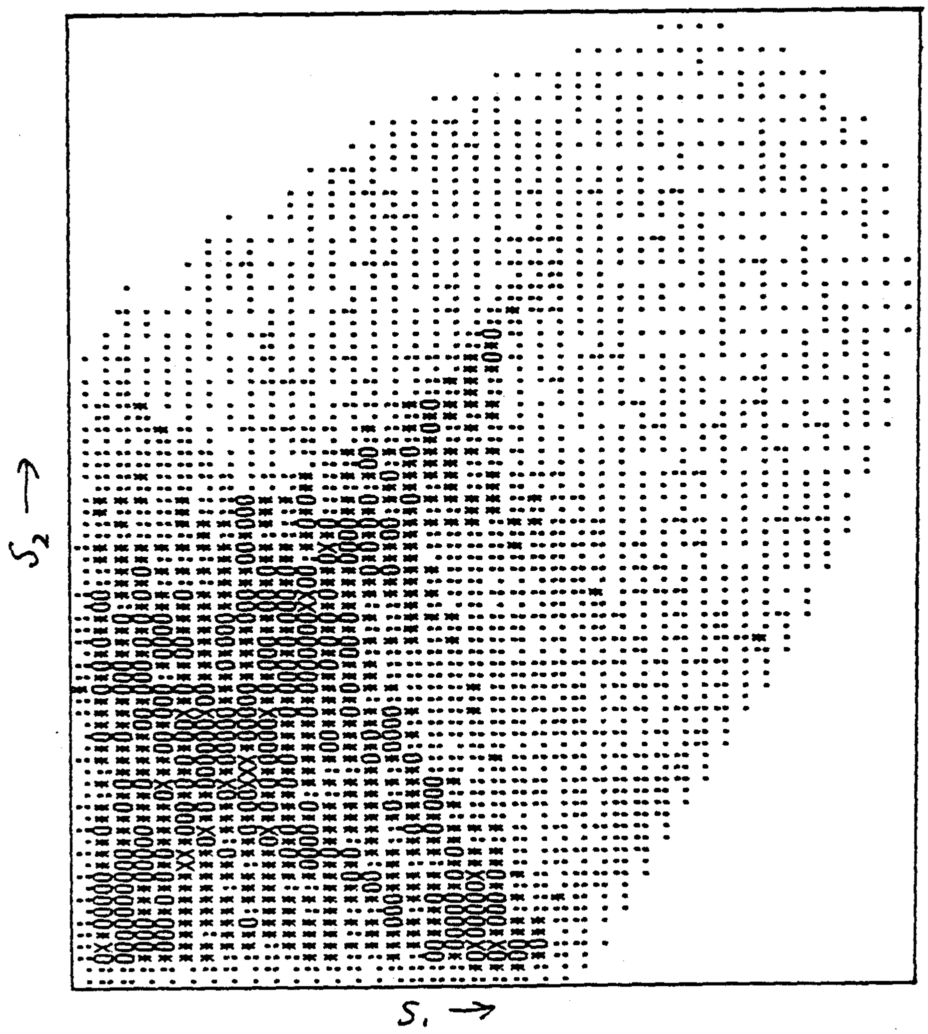
```
1
enter alpha, psi1, psi2
```

ED-CF
$\beta = 54$



enter alpha, psi1, psi2

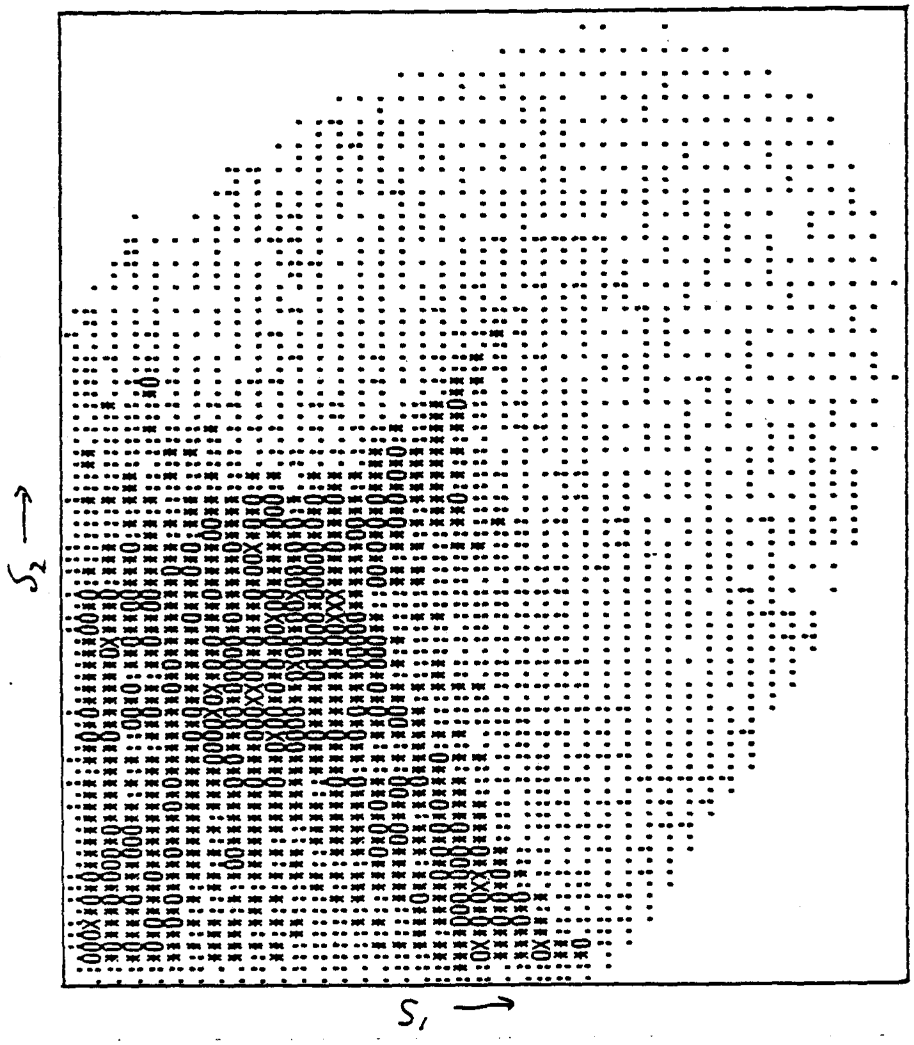
ED-CF
$\beta = 59°$



enter alpha, psi1, psi2

ED-CF

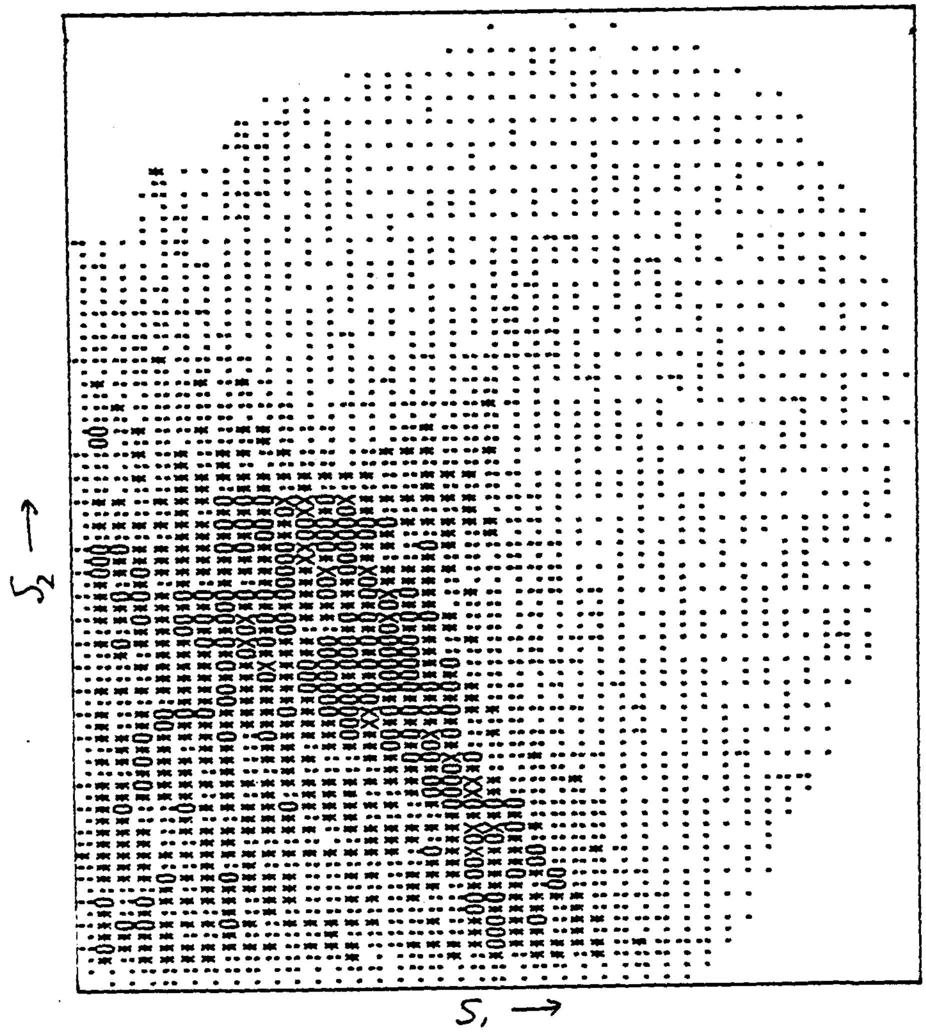
$\beta = 64^\circ$



enter alpha, psi1, psi2

ED-CF

$\beta = 69^\circ$



```
enter alpha, psi1, psi2
```

Appendix C
Coherence/Attenuation Lengths for Some Noise Sources

Source	Frequency	Characteristic Size
Acoustic[1] Wind	0.01–1.0 Hz	$\leq$ 0.3 coherence at 40 m
Thunder	1.0–2.5 Hz	$\approx$ 1 km for overhead storms
Seismic[2]	0.5 Hz 1.0 Hz 2.0 Hz	10 km 1 km $\leq$ 0.5 km
Extensive Air Showers[3]		
e^-	impulsive	700 m (density of $1/m^2$)
μ	impulsive	$\approx$ 1 km for 1 GeV
Electrical Transmission Lines[4]	60 Hz and harmonics	$\approx$ 150km

1. Posmentier, Eric, *J. Geo. Res.* **79**, p. 1755 (1974).
2. Dahlman, O. and Israelson, H. *Monitoring Underground Nuclear Explosions*, Elsevier (1977).
3. Galbraith, W., *Extensive Air showers*, Academic Press, (1958).
4. The 150 km figure is an average transmission line length based on a table in *EPRI Transmission Line Reference Book*, showing the largest transmission lines of various utility companies. It is not a coherence or attenuation length.

Appendix D
Antenna Beam Pattern Half-Width

Consider a detector that is looking at sources distributed uniformly in space — e.g. sources at and beyond the Virgo cluster. Then the number of sources per unit solid angle $d\Omega$ and per unit dimensionless amplitude dh will be

$$\frac{dN}{dh\,d\Omega}=\frac{\text{const}}{h^4} \; . \tag{D1}$$

For sources near the zenith and nearly underfoot the antenna beam pattern function will have a zenith-angle (θ) dependence

$$F(\theta)=\cos\theta+0(\theta^4) \; ,$$

since the two terms in the exact expression for F vary with θ as $\cos\theta$ and as $\frac{1}{2}(1+\cos^2\theta)=\cos\theta+0(\theta^4)$. Because the signal-to-noise ratio for a source is $\sigma\propto hF$, Eq. (D1) translates into

$$\frac{dN}{d\sigma\,d\cos\theta}=\frac{\text{const}\times\cos^3\theta}{\sigma^4} \; . \tag{D2}$$

This angular distribution puts half the observed sources inside an angle

$$\theta_{\frac{1}{2}}=\cos^{-1}(2^{-1/4})=32\,\text{degrees} \; . \tag{D3}$$

Since $\frac{1}{2}(1+\cos^2\theta)$ is somewhat larger than $\cos\theta$ at large θ, this estimate of $\theta_{\frac{1}{2}}$ is a bit too small; we shall use the slightly larger estimate

$$\theta_{\frac{1}{2}}=35\,\text{degrees} \; . \tag{3'}$$

Note that sources at the zenith angle $\theta_{\frac{1}{2}}$ have their signal-to-noise ratios debilitated, due to not being overhead, by $F(\theta_{\frac{1}{2}})\cong 2^{-1/4}=0.84$ — i.e. a 16% debilitation.

Appendix E.
Information that can be Extracted from a Gravity Wave with Various Site and Detector Configurations

The amount of information that can be extracted from a given set of gravity-wave observations depends on the configuration of the detectors and sites. In this appendix we describe several different configurations and attempt to estimate the science that could be accomplished with each. Appendix F contains the results of some numerical calculations that were performed to get a feeling for what could be accomplished with two of the specific cases. The configurations are described by two parameters: the number of individual sites, and the number of distinct detectors ("L's").

2 Sites, 2 L's

The first configuration for the LIGO will be two sites and two L's. This gives two time series and one time delay $\Delta\tau$. The time delay locates the position of the source on the sky to within a ring that is centered on the line between the sites and has angular radius $\Theta=\cos^{-1}(c\Delta t/D)$, where D is the distance between the sites. The width of the ring is determined by the precision of the timing measurement.

For a periodic source, the location within the ring and the polarization of the source can be determined by watching the observed signal evolve with time. (A method for determining the polarization and the location with a single antenna has been worked out in detail [Jeff Livas, PhD thesis, 1987].) Thus, even this simple configuration is sufficient to extract the astrophysics provided that one has a definite detection with a good signal to noise ratio.

For a burst source, the polarization information cannot be extracted without more precise information about the location of the source. If the location can be determined, by comparison with optical observations for example, the two wave forms may be extracted, in principle, as follows: define the + mode as that which maximally excites the first L; then, with renormalization by a direction-dependent factor, the measured time series for the first L is $h_+(t)$. Multiply this $h_+(t)$ by the direction-dependent factor that describes its coupling to the second L, and subtract the result from the second L's time series. The result, after direction-dependent renormalization, will be $h_\times(t)$. However, if the two L's have been optimally aligned (coincident projection) as we advocate, the second L like the first will have little sensitivity to $h_\times(t)$, and this procedure will produce mostly noise.

For a stochastic source, the cross correlation of the two detectors with appropriate time delays yields the spectral density for one polarization state and for a ring of directions on the sky.

Thus it is that our initial configuration, although optimized for gravity-wave discovery, extracts only half of the waveform information from burst sources and only a small portion of the information from an anisotropic stochastic background. For periodic sources of good signal to noise ratio our initial configuration is adequate to extract all the information carried by the wave.

2 Sites, 3 L's

One possible upgrade, after gravity waves have been detected, is to add at one of the original sites a second L oriented at 45 degrees with respect to one the first. With the two L's at the common site the two waveforms can be determined rather easily, if the direction of the source is known:

$$h_+=2(1+\cos^2\theta_s)^{-1}(s_1\cos2\phi_s-s_2\sin2\phi_s)\ ,\ \ h_\times=(\cos\theta_s)^{-1}(s_2\cos2\phi_s+s_1\sin2\phi_s).$$

where s_j are the strains $\Delta L_j/L_j$ measured by the two interferometers. As before, with only one time delay, the location of the source is not known without additional information.

2 Sites, 4 L's

This case is discussed quantitatively in Appendix F. It appears that, if the sites are as far apart as Edwards and Columbia so their planes are separated by an angle $\beta \gtrsim 35$ degrees, then the four time series from the two sites provide enough information to determine, with modest precision, the direction to the source and the two wave forms. Thus, in principle this configuration is as good as the 3-Site, 4-L one (below); though in practice it is less accurate and less robust (see Appendix F).

3 Sites, 3 L's

With three separate sites and a single L at each site, there are three time series and from them two independent time delays that can be observed. The time delays can be used to localize the source to the intersection of two finite-width rings on the sky, which in general is two patches. It is still undetermined how much further one could proceed with such a system. It seems reasonable to suppose that the three measured time series plus two possible locations for the source could be used to develop two different models of the two polarization waveforms, one for each patch in the sky. An obvious contradiction in one of the models or an extra piece of information from other observations would be needed to determine which model was more likely to be correct.

3 Sites, 4 L's

This configuration, like the 2-Site, 4-L one, is discussed quantitatively in Appendix F. Both configurations can determine, in principle, the position and both wave forms; but this configuration is more robust and more accurate.

4 Sites, 4 L's

A network of four single L's at four separate sites could do a significantly better job of unambiguously extracting the full information in the wave than 3 sites and 4 L's – providing the four sites do not lie nearly in the same plane [more precisely, providing their volume figure of merit, Eq. (7), is large]. The three independent time delays could be used to localize the source to a single patch on the sky, and the four measured time series should contain enough information to extract the two polarization waveforms. The best method for obtaining the solution has not yet been worked out in detail.

Relative Importance of Position and Polarization Information

The relative importance of position information and polarization information is difficult to quantify because it depends on the type of source being studied and on the presence or absence of additional information. The consensus of this working group is that position information is slightly more important than polarization information because the position of the source is explicitly needed to extract the polarization information from two L's located at a single site, and because the position is needed to connect gravitational observations with the rich body of knowledge compiled by other types of astronomy. The results presented in Appendix F seem to suggest that measurements of either polarization or time delays can be used to determine the position of a source, but time delays tend to be more accurate and more robust.

Appendix F
Comparison of 2-Site, 4-L Configuration with 3-Site, 4-L Configuration

One of the key issues analyzed by the committee is the question of what enhancements to the initial "2 L" LIGO configuration might be required to extract the maximum amount of information from gravitational wave signals. In particular, might the LIGO project want to add additional L's either at one or even both original sites?

Although we originally thought of the question in terms of measuring the polarization and determining the complete gravitational waveform, it quickly became clear that these measurements are inextricably linked with determination of the angular position of the gravitational wave source. This is because polarization is measured by examining ratios of signals in different antennas. The amplitude response of a single antenna to a linearly polarized wave is proportional to

$$F = \tfrac{1}{2}(1+\cos^2\theta)\cos 2\phi \cos 2\psi - \cos\theta \sin 2\phi \sin 2\psi \quad , \qquad \text{(F.1)}$$

where θ is the source's zenith angle, ϕ is the source's azimuth measured from one of the L's legs, and ψ is an angle specifying the orientation of the source's polarization axes. Extraction of the polarization angle ψ involves knowledge of the position angles θ and ϕ.

Previous discussions of position determination have assumed 4 or more individual L's, each at a separate location. The direction of travel of the gravitational wave must explain the arrival time of the signals at the different sites. With 4 sites, the position is restricted to a single region on the sky, whose size depends on errors in the timing. We have not seen a discussion of extraction of the two polarization waveforms, but one method can easily be imagined. Because of their different locations on the earth and different orientation angles about the local vertical, each antenna will be sensitive to a different combination of the two wave forms h_+ and $h_\times$ coming from the position of the source. Decomposition of the 4 time series into the 2 orthogonal waveforms should be straightforward. (An error analysis of this procedure would be worthwhile, but we have not done it yet.)

We were particularly interested in what could be accomplished from only 2 sites. One can imagine adding a second "orthogonal" L (rotated by 45 degrees from the first) at each site. Then there are as many L's as in the "classical" configuration, but the information takes a different form. Instead of 3 independent time delays, we have only 1. However, the ratios of the signals in each colocated pair of L's also provide useful information. (In principle, the ratios between separated L's contain the same sort of information, but this is not useful until accurate position information determines the time delay between them.)

To test this method, we assume that a gravitational wave signal comes from a well-defined spot on the sky, and that it has a fixed linear polarization, i.e. a fixed ratio $h_+/h_\times$ (either throughout the burst, or within a subsection which we can detect with sufficient signal-to-noise ratio). We compute what would be the signal ratios and time delay if the the wave came from each position in a two-dimensional grid on the sky, with each polarization from a third grid axis. Each point in this set is compared with the "measured" signal ratios and time delay. The set of grid points which match the measurements (within a specified precision) constitute the error box.

We compare the error boxes generated by this 2-site, 4-L method with what could be achieved with 4 L's at 3 sites. In the 3-site case, one of the sites has a 45 degree pair of antennas as in the 2-site method, while at the other two sites there is just a single L; and the measurables are two independent time differences, and one signal ratio from the site with two L's. To test the 3-site method, we again search a grid in right ascension, declination, and polarization angle, comparing the predicted values of time delays and ratio from each grid point with the "measured" value.

We compute two different measures of the size of the error boxes. One is the volume, in the three-dimensional space of angles. The other is the area on the sky, projecting out the polarization dimension.

For specificity, we have chosen the Edwards, Columbia, and LSU sites for the 3-site, 4-L configuration. Edwards and LSU are the locations used for the 2-sites, 4-L configuration. We assume that time differences can be determined to 0.3 msec, and that signal ratios can be determined to 30%. To make this last specification reasonably fair, we restrict our comparisons to situations where all antenna responses are greater than 0.2 times the maximum response (at the zenith with optimal polarization).

A table comparing the two methods for a number of examples is given below.

TABLE F-1: Error Box Areas

Source (RA,DEC,PA)	2-sites (sq. deg.)	3-sites (sq. deg.)
20,0,45	1224	99
30,0,0	324	65
40,0,0	414	61
50,0,0	455	52
120,0,45	408	52
130,0,45	377	68
140,0,45	317	92
30,-40,0	567	35
40,-40,0	588	23
50,-40,0	511	36
100,-40,0	441	23
110,-40,0	615	26

TABLE F-2: Error Box Volumes

Source (RA,DEC,PA)	2-sites (cu. deg.)	3-sites (cu. deg.)
20,0,45	6974	1316
30,0,0	1347	162
40,0,0	1526	257
50,0,0	1539	218
120,0,45	1467	456
130,0,45	2118	933

140,0,45	2447	2076
30,-40,0	2073	258
40,-40,0	2504	168
50,-40,0	2126	216
100,-40,0	1412	185
110,-40,0	2724	234

Figures F-1a and F-1b show maps of the error boxes obtained by the two methods for the 50,0,0 source (fourth down in each table).

The most striking feature of this exercise has been that the 2-site method works at all well. With the chosen values of precision, the 3-site method has a substantial edge over the 2-site. The detailed numerical results depend sensitively on the precision to which ratios and timing are assumed to be measured, since in the 2-site method, the error box volume will scale as (ratio precision)$^2\times$ (timing precision), while in the 3-site method the volume is proportional to (ratio precision)$\times$(timing precision)^2. The 2-site method requires, in order to work at all, that the sites not lie in the same plane; and the farther apart they are, the better it works. However, even if the sites are as far apart as Edwards and Columbia, the 3-site method still has a clear edge.

Because the 2-site method works to a fair extent, it is hard to draw a clear lesson concerning the Columbia site, where a second L is precluded. One way of looking at the results is to say that there is no scientific capability which the LIGO would lack by using Columbia, so long as we consider establishing a third site as a viable option (or if we believe the rest of the world will build at least two sites). A different interpretation of the results could be that building extra L's at both sites, which might be cheaper to build and easier to manage than a three site system, can do science that is in some way comparable. This line of argument would suggest that we shouldn't give up in advance the possibility to make the choice to have 4 L's at only 2 sites, and therefore Columbia lacks a valuable feature.

There is an important weakness of the 2-site, 4-L method which is not made clear by this comparison. That is the dependence of the technique on a constant linear polarization. If the source has substantially elliptical polarization, as in the signal from a coalescing binary, then we can only apply the 2-site method if we can break the signal up into short chunks during which the polarization is approximately constant. This means we require substantially larger signal-to-noise ratios for this method than for a timing technique. Even if the signal is linearly polarized, we need a large signal-to-noise ratio to check that that is the case.

By contrast, determinations of position by time differences demand only modest signal-to-noise ratios. This is the chief virtue of 3-site and 4-site techniques. To determine the polarization as a function of time still requires the same high signal-to-noise ratio as in the 2-site method. But, at least the use of multiple time differences allows the extraction of position information without demanding a simultaneous solution for the polarization. With the 2-site 4-L method, one needs enough information to solve the whole problem all at once.

The state of gravitational wave astronomy outside the U.S. will play an important role in future decisions about expansion of the LIGO. If there is even one comparable antenna elsewhere, the world network will consist of 3 L's at 3 sites, which is capable of doing most of the science of the 4-L configurations studied here. (See discussion in the body of this report, and Tinto, 1987a,b.) Then the addition of a second L at even one of the original LIGO sites will give the full capability studied here. Alternatively, establishing a third single L in the U.S. would give the world a 4-site network, capable of unambiguous position and polarization waveform determination.

If there are two sites comparable to the American sites elsewhere in the world, there would be very little impetus to add additional L's here, unless it were for other purposes, such as better detection of high frequency stochastic backgrounds.

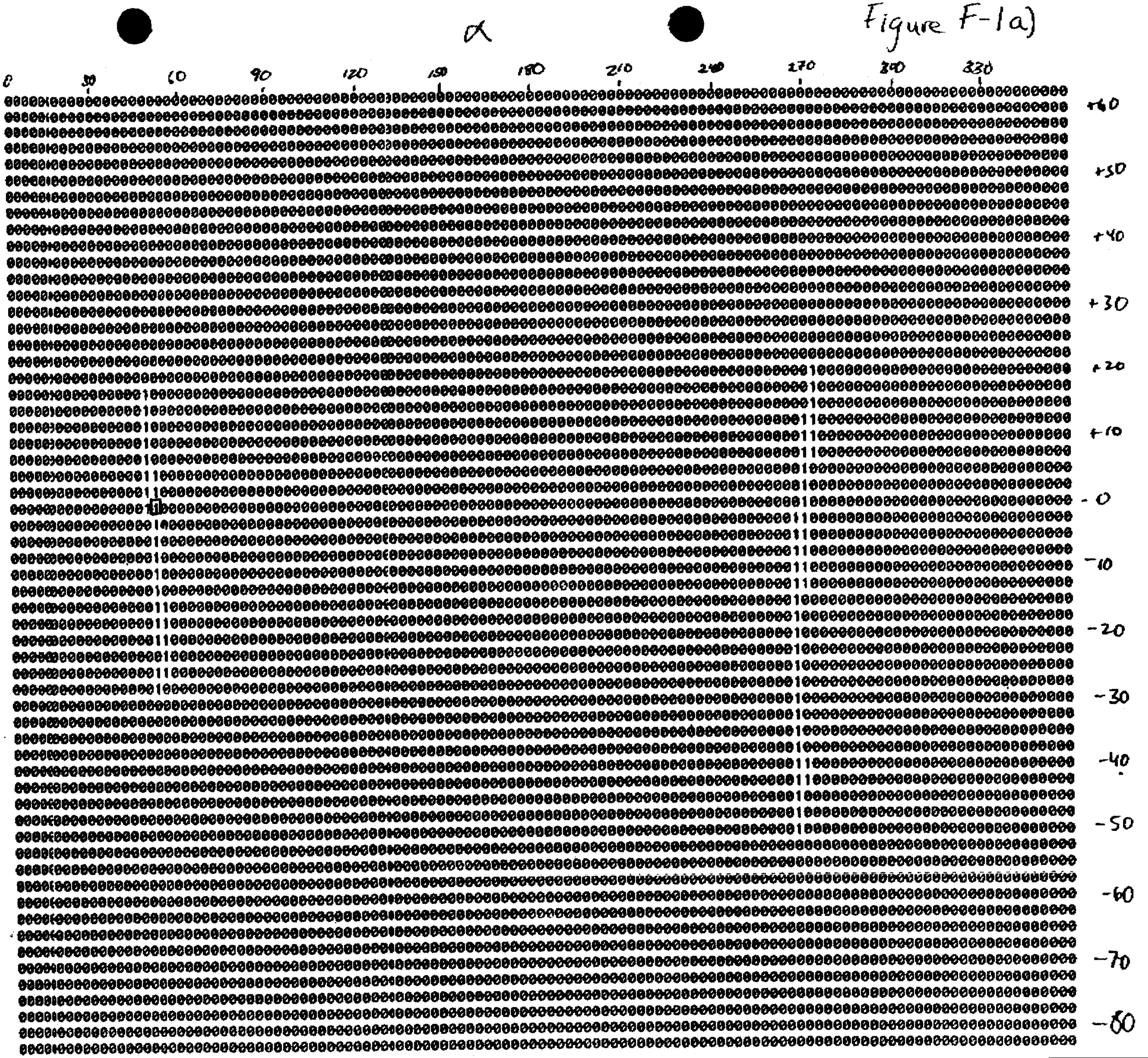
Figure Captions

Figure F-1a: A map of the sky showing source positions allowed by the 2-site, 4-L method for a particular set of signal ratios and one time delay. The input data corresponded to a source at RA$\equiv\alpha=50$ degrees, Dec$\equiv\delta=0$, PA$\equiv\psi=0$. Two pairs of L's, at Edwards Air Force Base and at Louisiana State University, were assumed. The bins marked "1" are allowed to within the specified precision, while bins marked "0" are ruled out. Polarization of the source at each position has been projected out in this map.

Figure F-1b: As above, but for the 3-site, 4-L method. The input data were time delays corresponding to L's at Edwards, Columbia, and LSU, plus a single signal ratio between a pair of 45-degree rotated L's at Edwards.

Figure F-1a)

Method 1
(2 sites
4 L's)



6

Figure F-1b)

Meth[illegible] 2 (3 sites, 4 L's)

α

0 30 60 90 120 150 180 210 240 270 300 330

```
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000 +60
001111000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
000111100000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000 +50
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000 +40
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000 +30
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000 +20
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000 +10
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
000000000000000010000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
000000000000000010000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
000000000000000010000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000 0
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000 -10
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000 -20
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000 -30
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000 -40
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000 -50
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000 -60
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000 -70
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000 -80
000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
```

δ

Appendix G
German Triangular Configuration Compared to Two 90-degree L's

In Sec. I.C.6 of the text we argue that it would not be wise to build one (or both) of our initial LIGO L's with a 60-degree opening angle, in preparation for a possible future upgrade into a German triangular vacuum system. Here we justify some of the statements made in that argument.

1. Sensitivities of Various Configurations

It can be shown that for a single L (our initial LIGO configuration at each site) the amplitude signal-to-noise ratio depends on opening angle α as $\sin\alpha$. Thus, for the same arm lengths, the initial 60-degree and 90-degree L's would have relative S/N's

$$\frac{\sigma_{60}}{\sigma_{90}}=\sin(60\mathrm{deg})=\frac{\sqrt{3}}{2}=0.87 \quad ; \qquad \text{(G.1)}$$

and this is true for all gravitational waves, regardless of direction and polarization (if the detectors are in the same plane and their bisectors are parallel).

After the upgrade of the 60-degree L to a triangle with one detector centered on each of the three vertices, and the upgrade of the 90-degree L by adding another 90-degree L rotated by 45 degrees to the first, the relative S/N's for equal arm lengths will be

$$\frac{\sigma_{\Delta}}{\sigma_{2\,90s}}=\frac{3}{2\sqrt{2}}=1.06 \quad ; \qquad \text{(G.2)}$$

and this again is true for all gravitational waves, regardless of direction and polarization, so long as the two configurations lie in the same plane. Thus, the upgrades bring the triangular configuration from a 13% lower amplitude sensitivity to a 6% greater amplitude sensitivities.

2. Relative Costs

The very rough estimates of costs quoted in the text are based on the assumption that two 90 degree L's will cost a total of 80 million dollars, with 2/3 of that cost length dependent and tied up in the arms, and 1/3 fixed and tied up in the end stations and corner stations. Correspondingly, the cost of one 4 km arm of one detector is presumed to be 13 million dollars, or 3.3 million dollars per km.

The upgraded configurations we compare are the "2L" configuration consisting of two 4-km L's with midstations comprising two additional 2-km interferometers, and the "triangle" configuration, three 4-km 60-degree interferometers. Midstations for half-length interferometers are included in the initial L as a local veto against accidentals such as outgassing bursts from one of the pipes. Midstations on the upgrade L, though not essential, have the desirable feature of providing two identical detectors that can be operated independently. The triangle has adequate redundancy without midstations. However, its initial 60-degree detector would require either midstations or the second of the three detectors from the start.

The triangle in its final form makes the most economical use of culverts or covers, accommodating three full-length detectors in just three arms; the final 2L configuration has four arms accommodating two full-length and two half-length interferometers. For a fair comparison, we estimate the cost of the triangle assuming that one vacuum pipe in the triangle will accommodate two interferometers, just as the half- and full-length interferometers share a common pipe in the 2L. This assumption differs from the proposed German design, which calls for two pipes. (The difference is attributable to our commitment from the start to allow multiple interferometers within the original facilities; the proposed German vacuum system can accommodate just one interferometer of the type they are considering.)

The arm cost, which includes pipes, pumps, tunneling, culverts and covers, is lower in the triangle by the cost of one 4-km arm, or 13 million dollars. Other differences between the two upgraded configurations will have a smaller influence on the construction cost. The 2L requires only one full-size vertex station and two full-power lasers (lower power lasers can be used for the half-length L's), compared to three vertex stations and three full-power lasers for the triangle. On the other hand, the triangle has greater design uniformity, fewer buildings (three or five instead of seven or nine), and 6% better sensitivity for the same arm length.

An intermediate configuration proposed by Drever calls for adding a hypotenuse to the original L and a bisecter from the vertex to the hypotenuse. The two inner L's of length 4 km $\times\sqrt{2}$ respond to the polarization orthogonal to the original L, and when their outputs are added (assuming sensitivity proportional to arm length) the signal-to-noise ratio matches that of the original L. The arm cost of this configuration is approximately the same as for the 2L (a total of 4.1 km additional arm length is needed for the upgrade) but the land and building requirements are similar to the triangle.

The triangular configurations (either the German design or Drever's proposal) offer the additional advantage of allowing the construction of interferometers of large enclosed area, useful for some applications that are still speculative. For example, a ring laser gyroscope on this scale would be a rotation sensor of unprecedented sensitivity, and might have geophysics applications. Ring interferometers might also be used to measure the magnetic component of gravitational waves, or as part of an experment to detect the earth's dragging of inertial frames.

As is argued in the text, we do not think the savings in upgrade cost inherent in the German design will be sufficient, in the American context, to justify the penalty paid

Appendix H

LIST OF SITES CONSIDERED

This is a fairly complete list of all the locations, both above and below ground, that were seriously considered as sites for a gravitational wave antenna. The earliest survey, conducted by Stone \& Webster Engineering Corporation considered only government installations and mines. Details of this survey are published in the 1983 "Blue Book" study prepared for the NSF. The 1984 JPL study also published a report titled "Site Selection Evaluation for a Gravity Wave Detector Facility". The survey labeled MIT was an in depth follow-up of selected areas near the East Coast conducted by primarily by Peter Saulson and Rainer Weiss. It has not been published. The LIGO survey was a follow up study of selected areas near the West Coast conducted primarily by Frank Schutz. All 50 states are included for completeness, but some states had no suitable sites on public land.

State	Installation	Survey	Good?	Comments
1) Alabama	Anniston Army Depot	S&W	N	Topography, land use
	Fort Rucker	S&W	N	Topography
	Fort McClelland	S&W	N	Topography
	Redstone	S&W	N	Topography, land use
2) Alaska				
3) Arizona	Luke Air Force Range	S&W/JPL	N	Bombing and Gunnery range
	San Cristobal Valley	S&W/JPL	Y	Private Land
	Somerton Area	S&W	N	Seismicity
	Yuma Proving Ground	S&W	N	Bombing/firing range
	Lakeshore Mine	S&W	N	0.2 km x 0.2 km
	Superior Mine	S&W	N	0.1 km x 0.3 km
4) Arkansas	Fort Chaffee Military Res	S&W	N	Topography
5) California	Beale Air Force Base	S&W	N	Topography, land use
	Bristol Dry Lake	S&W/JPL	Y	Remote, BLM land
	Camp Pendelton Marine Base	S&W	N	Topography
	China Lake Naval Weapons	S&W/JPL	N	Seismicity
	Clark Dry Lake Radio Obs.	S&W/JPL	N	Seismicity
	Edwards AFB	S&W	Y	Primary West Coast Site
	Fort Irwin Military Res.	S&W	N	Topography
	Fort Ord Military	S&W	N	Topography, land use
	Hunter Ligget Military Res.	S&W	N	Topography, seismicity
	Miramar Naval Air Station	S&W	N	Land use
	National Parachute Test Range	S&W	N	Seismicity
	Owens Valley	S&W	N	Insufficient space
	Saline Valley Dry Lake	S&W	N	Inaccessible
	Twnentynine Palms Marine Base	S&W	N	Topography
	Palen Lake	JPL	Y	No infrastructure
	Goldstone	JPL	Y	
	Bishop Mine	S&W	N	0.6 km x 1.0 km
	Soda Lake	LIGO	N	BLM land
	Hawes	LIGO	N	Mining & Petroleum claims
	Harper Lake	LIGO	N	Land use
	North Harper Lake	LIGO	N	Near a fault, Drainage
	Coyote Lake	LIGO	N	Flooding, Land use
6) Colorado	Alamosa Area	S&W/JPL	Y	Privately owned
	D.O.T. Exp. Train Track	S&W	N	Land use

	Fort Carson	S&W	N	Topography
	Rocky Mountain National Ars.	S&W	N	Topography
	Henderson Mine	S&W	N	0.2 km x 0.3 km
	Henderson East Tunnel	S&W	N	No significant "L" passages
7) Connecticut	Entire State	S&W	N	Topography, land use
8) Delaware				
9) Florida	Eglin AFB	S&W/JPL	N	Land Use
10) Georgia	Fort Benning	S&W	N	Topography
	Fort Gordon	S&W	N	Topography
	Fort Stewart	S&W/JPL	N	Tank Training Ground
11) Hawaii				
12) Idaho	Idaho National Eng. Lab.	S&W/JPL	Y	Backup site
	U.S. Sheep Exp. Station	S&W	N	Topography
	Bunker Hill Mine	S&W	N	0.8 km x 0.9 km
	Lucky Friday Mine	S&W	N	0.4 km x 0.8 km
13) Illinois	U.S. Gypsum Co. Mine	S&W	N	max 0.6 km x 0.6 km
	Mississippi Lime Mine	S&W	N	0.7 km x 0.7 km
	Chicago Mine	S&W	N	1.6 km x 1.6 km, extensive maintenance
	Praire du Rocher Mine	S&W	N	0.3 km x 0.4 km
	Vulcan Mine	S&W	N	0.4 km x 0.4 km
	Fermi Lab	MIT	N	Insufficient space
14) Indiana	Camp Atterbury	S&W	N	Topography, land use
	Crane Naval Weapons Support	S&W	N	Topography
	Jefferson Proving Ground	S&W	N	Topography
	Shoals Mine	S&W	N	0.4 km x 0.4 km
	Chicago Metro Sewer Comm.	S&W	N	0.8 km x 1.4 km (in use, though)
	Coal Mines -- general	S&W	N	0.2 km x 0.2 km
15) Iowa	Sperry Mine	S&W	N	0.3 km x 0.3 km
16) Kansas	Fort Riley	S&W	N	Topography, land use
17) Kentucky	Blue Grass Army Depot	S&W	N	Land use
	Fort Knox Army Res.	S&W	N	Topography
	Dravo Mine	S&W	N	0.3 km x 0.3 km
	Black River Mine	S&W	N	0.4 km x 0.5 km
	Princeton Mine	S&W	N	0.6 km x 0.6 km
	Mullins Mine	S&W	N	0.5 km x 0.5 km
	Frederick Mine	S&W	N	1.0 km x 1.1 km
18) Louisiana	Fort Polk	S&W	N	Topography
19) Maine	Columbia	MIT/JPL	Y	Primary East Coast Site
	Saponac (Greenfield Twnshp)	MIT/JPL	N	Granite
	Presque Isle AFB	MIT	N	Remote, Land use
20) Maryland	Aberdeen Proving Ground	S&W	N	Insufficient space
	National Agricltural Center	S&W	N	Insufficient space

21) Massachusetts	Fort Devins	MIT	N	Topography
	Westover AFB	MIT	N	Insufficient space
	Otis AFB	MIT	N	Bombing/firing range
	Natick Army Res. Labs	MIT	N	Insufficient space
	Taunton	MIT/JP:	N	Drainage, Insufficient space
22) Michigan	Camp Grayling	S&W	N	Topography
	White Pine Mine	S&W	N	0.3 km x 0.9 km
	Detroit Mine	S&W	N	1.0 km x 1.0 km
23) Minnesota	Camp Ripley	S&W	N	Topography, Drainage
24) Mississippi				
25) Missouri	Fort Leonard Wood	S&W	N	Topography
	Randolph Mine	S&W	N	1.4 km x 1.6 km
	Buick Mine	S&W	N	0.3 km x 4.0 km
	St. Genevieve Mine	S&W	N	0.6 km x 0.6 km
	Magmont Mine	S&W	N	0.3 km x 2.0 km
	Viburnum Mine	S&W	N	0.3 km x 1.5 km
	Fletcher Mine	S&W	N	0.6 km x 2.0 km
	Brock Mine	S&W	N	0.4 km x 0.7 km
	Heath Mine	S&W	N	0.3 km x 3.0 km
26) Montana				
27) Nebraska	Entire State	S&W	N	Topography, Land use
28) Nevada	Nellis Bombing and Gunnery	S&W	N	Topography, Drainage, Land use
	Hidden Valley	LIGO	N	Flood hazard
	Dry Lake	LIGO	N	Land use
29) New Hampshire	Entire State	S&W	N	Topography, Land use
30) New Jersey	Entire State	S&W	N	Topography, Land use
	Sterling Hill Mine	S&W	N	0.1 km x 0.1 km
31) New Mexico	Fort Bliss	S&W/JPL	Y	
	Sandia	S&W	N	Topography
	Plains of San Augustin (VLA)	S&W/JPL	Y	Restricted to triangle by land use
	White Sands	S&W/JPL	Y	
	Eddy Mine	S&W	N	0.7 km x 0.8 km to be reactivated
	Nash Draw Mine	S&W	N	1.5 km x 1.5 km
	Mississippi Chem. Mine	S&W	N	0.4 km x 0.4 km, abandoned
	IMC Mine	S&W	N	0.2 km x 0.2 km
	PCA Mine	S&W	N	0.2 km x 0.3 km
32) New York	Entire State	S&W	N	Topography, Land Use
	Retsof Mine	S&W	N	1.0 km x 1.0 km
	Cayuga Mine	S&W	N	0.9 km x 1.0 km
	Seneca Mine	S&W	N	0.6 km x 0.7 km
33) North Carolina	Entire State	S&W	N	Topography, Drainage, Land use
34) North Dakota				
35) Ohio	Cleveland Mine	S&W	N	1.7 km x 1.7 km
	U.S. Corps of Eng.	S&W	N	Underground shelter study
	Jonathon Mine	S&W	N	0.8 km x 0.9 km
	Fairport Mine	S&W	N	0.6 km x 0.9 km
	Barberton Mine	S&W	N	0.6 km x 0.8 km
	Zanesville Mine	S&W	N	0.7 km x 1.1 km
	Paynesville Mine	S&W	N	0.6 km x 0.9 km

36) Oklahoma	Fort Sill	S&W	N	Topography
	Naval Ammunition Depot	S&W	N	Topography
37) Oregon				
38) Pennsylvania	Bethlehem Corp.	S&W	N	max 0.5 km x 0.5 km
	Peabody Coal	S&W	N	max 0.2 km x 0.3 km
	Conoco	S&W	N	max 0.7 km x 0.5 km
	Consolidated Coal Corp.	S&W	N	max 0.4 km x 0.2 km
	U.S. Steel	S&W	N	max 0.3 km x 0.3 km
	U.S. Corps of Engineers	S&W	N	underground shelter study
39) Rhode Island	Entire State	S&W	N	Topography, Land use
40) South Carolina	Fort Jackson	S&W	N	Topography
	Savanah River Plant	S&W	N	Topography, Land use
41) South Dakota	Homestake Mine	S&W	N	0.3 km x 0.4 km
42) Tennessee	Arnold Engineering Dev.	S&W	N	Topography
	Fort Campbell	S&W	N	Topography
	Oak Ridge	S&W	N	Topography
	Mascot Mine	S&W	N	0.4 km x 0.4 km
	New Market Mine	S&W	N	0.2 km x 0.3 km
	Gleason Mine	S&W	N	0.3 km x 0.3 km
	Gordonsville Mine	S&W	N	0.3 km x 0.3 km
43) Texas	Fort Hood	S&W	N	Topography
	Lackland	S&W	N	Insufficient space
44) Utah	Desert Range Exp. Station	S&W	Y	
	Great Salt Lake Desert	S&W/JPL	Y	
	Lynndl	S&W/JPL	Y	BLM land
	Park City Mine	S&W	N	0.3 km x 0.3 km
	Bat Tunnel	S&W	N	12.8 km (one tunnel only: water tunnel)
	Hades Tunnel	S&W	N	7.2 km (one tunnel only: water tunnel)
	Dugway Proving Ground	JPL	Y	Remote, No infrastructure
	Skull Valley	LIGO	N	Remote, No infrastructure
	Aranonite	LIGO	N	Remote, No infrastructure
45) Vermont	Entire State	S&W	N	Topography, Land use
46) Virginia	Fort Eustis	S&W	N	Insufficient space
	Fort A.P. Hill	S&W	N	Topography
	Fort Pickett	S&W	N	Topography
	Quantico Marine Air Base	S&W	N	Topography
	Kimballton Mine	S&W	N	0.2 km x 0.3 km
47) Washington	Fort Lewis	S&W	N	Seismicity
	Hanford Reservation	S&W	N	Topography, Land use
	Yakima Firing Center	S&W	N	Bombing/firing range
	Pend Orielle Mine	S&W	N	0.1 km x 0.2 km
48) West Virginia	Consolidated Coal (mine)	S&W	N	max 0.2 km x 0.2 km
49) Wisconsin				
50) Wyoming	Westvaco Mine	S&W	N	0.2 km x 0.3 km
	Alchem Mine	S&W	N	0.2 km x 0.4 km
	Carbon County Coal Co.	S&W	N	0.6 km x 0.8 km, no real passages

Notes:

1) All mines actively used unless otherwise noted: distances are line-of-site

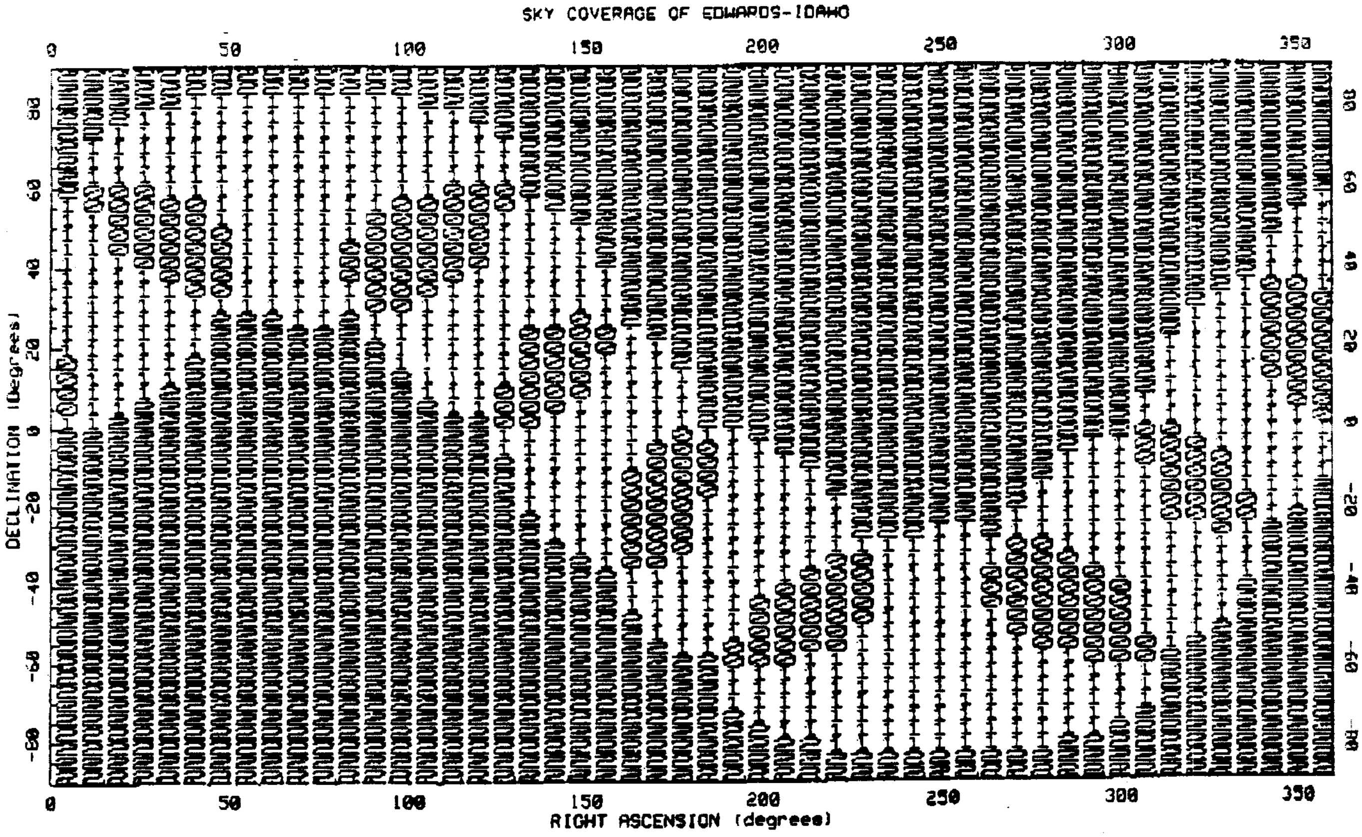
Appendix I
Sky Coverage Maps

In this appendix we present maps that illustrate the sky coverage achieved by pairs of coincident-projection oriented L's at various possible LIGO sites (Edwards-INEL, LSU-INEL, Edwards-Columbia, Columbia-INEL, and Edwards-LSU). Note that there is only slight variation in sky coverage from one pair of sites to another.

Figure Captions

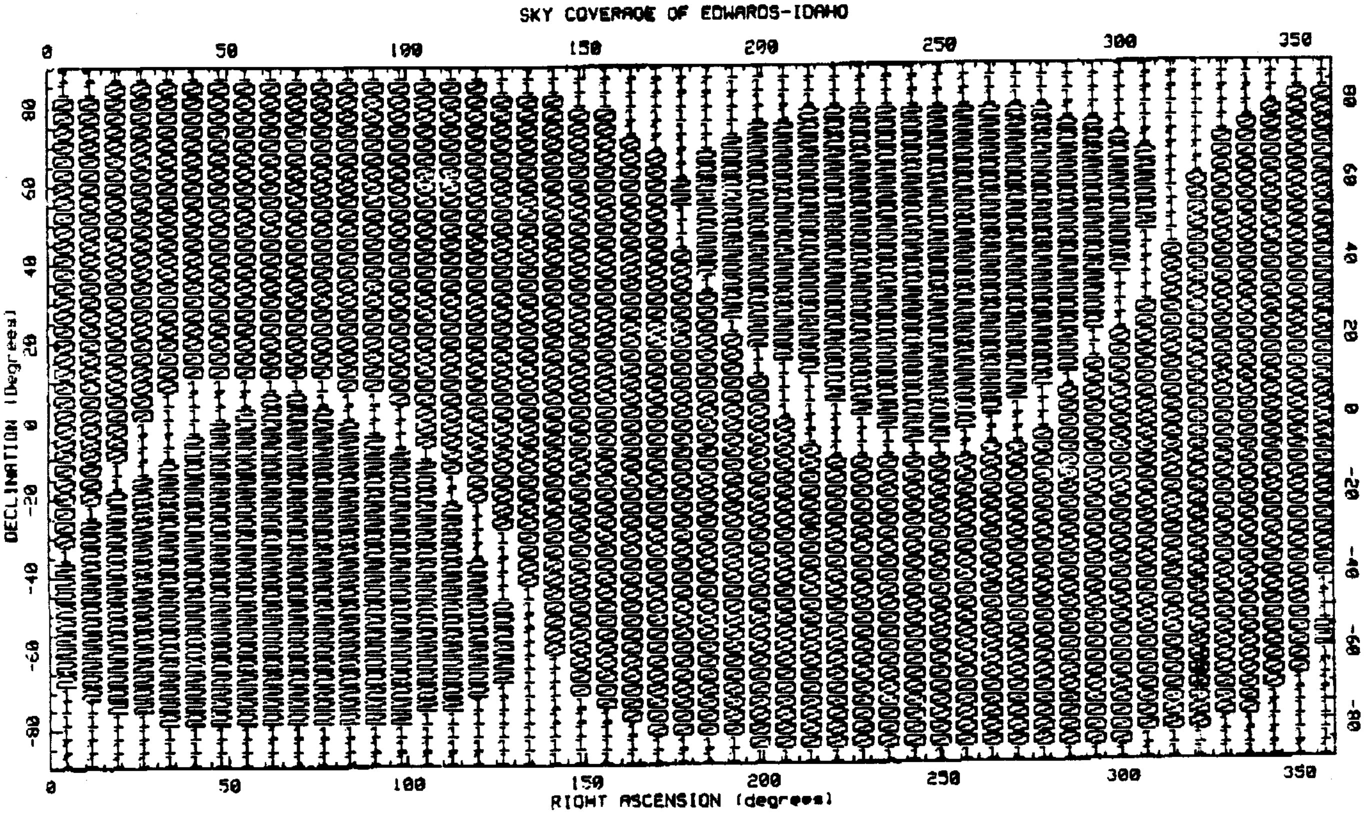
Figures I.1 - I.5. These maps show, at each point on the sky, the number of L's in the pair (0, 1, or 2) at which a given threshold is exceeded by the polarization-averaged signal-to-noise ratio $\overline{\sigma}$. The thresholds are measured in units of the signal-to-noise ratio that the source would have had were it directly overhead, with optimal polarization, $\sigma_{\rm opt}$. Because of the polarization averaging in $\overline{\sigma}$, if the source were overhead, it would have $\overline{\sigma}/\sigma_{\rm opt}=1/\sqrt{2}=0.71$. The thresholds chosen are $\overline{\sigma}/\sigma_{\rm opt}=0.5$ (30% below this maximum of 0.71), and $\overline{\sigma}/\sigma_{\rm opt}=0.33$ (54% below the maximum). With the 0.5 threshold much of the sky is not covered. Lowering the threshold to 0.33 covers most of the sky with both detectors.

Figures I.5 - I.10 These maps show, at each point on the sky, the signal-to-noise ratio $\overline{\sigma}_{\rm min}$, averaged over polarization, that a source at that location would have if measured from the least sensitive of the two sites, divided by the signal-to-noise ratio $\sigma_{\rm opt}$ that the source would have if it were directly overhead: $\overline{\sigma}_{\rm min}/\sigma_{\rm opt}$. As above, because of the polarization averaging, the largest this ratio can be is $1/\sqrt{2}=0.71$.



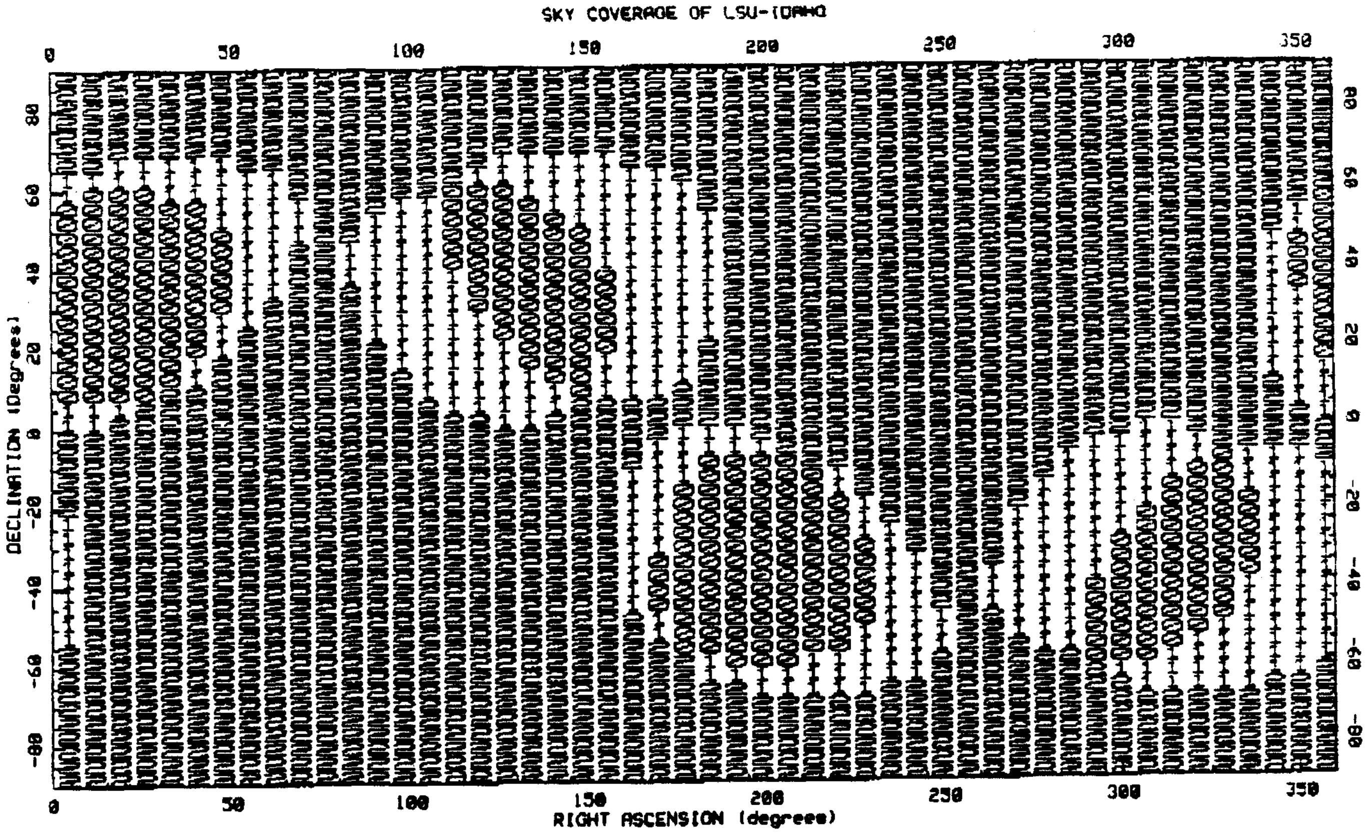
Number of antennas with sensitivity > 33.00 % of maximum
Averaged over polarization

Figure I.1



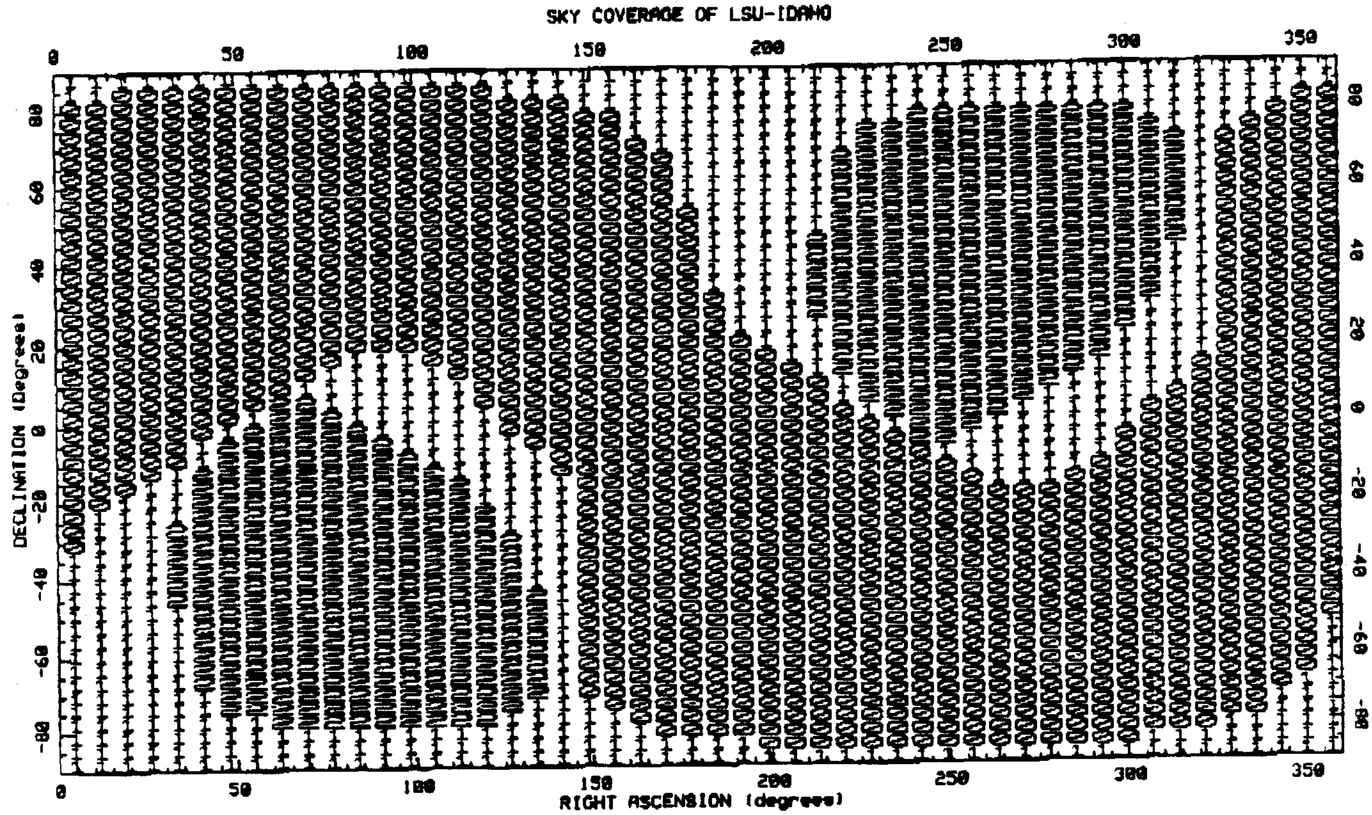
Number of antennas with sensitivity > 50.00 % of maximum
Averaged over polarization

Figure I.1b



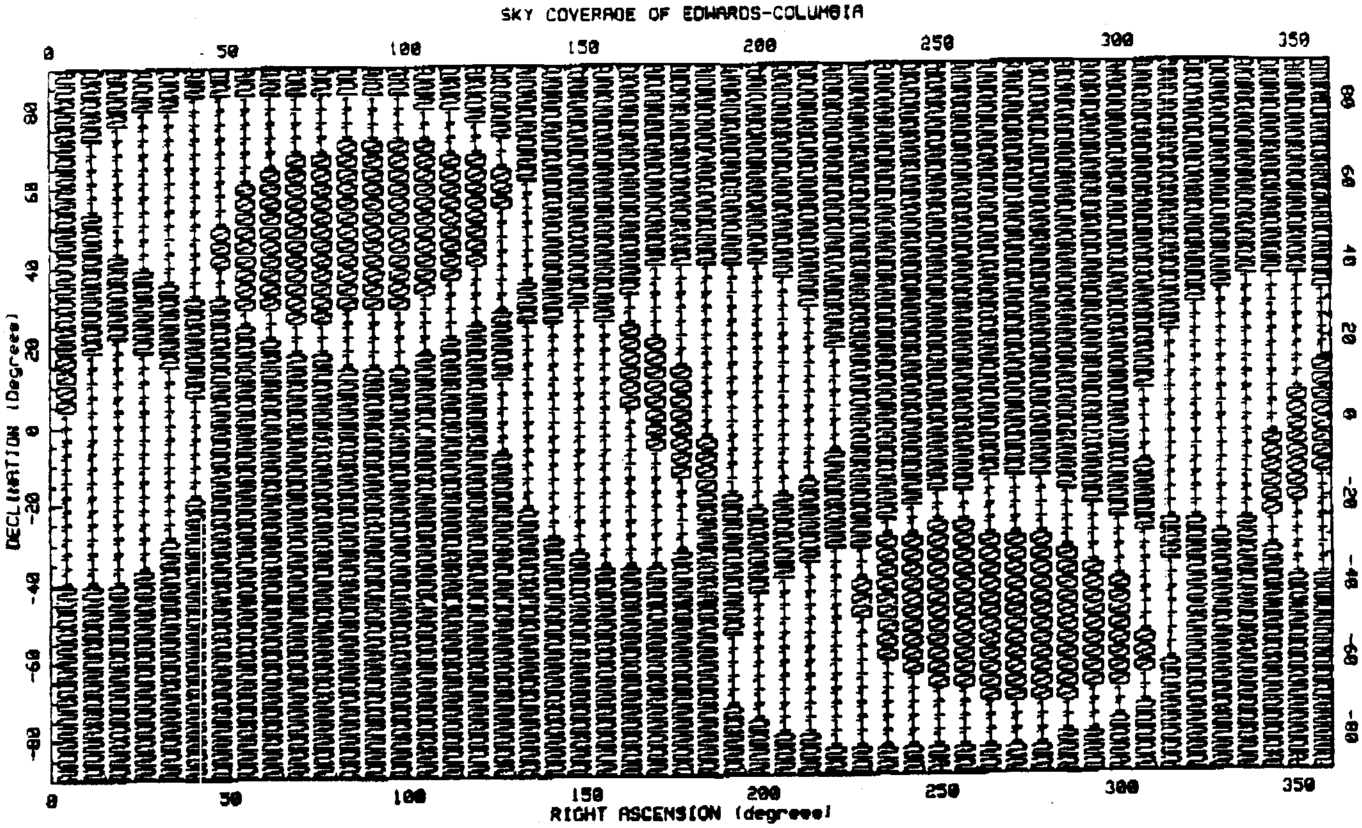
Number of antennas with sensitivity > 33.00 % of maximum
Averaged over polarization

Figure I.2a



Number of antennas with sensitivity > 50.00 % of maximum
Averaged over polarization

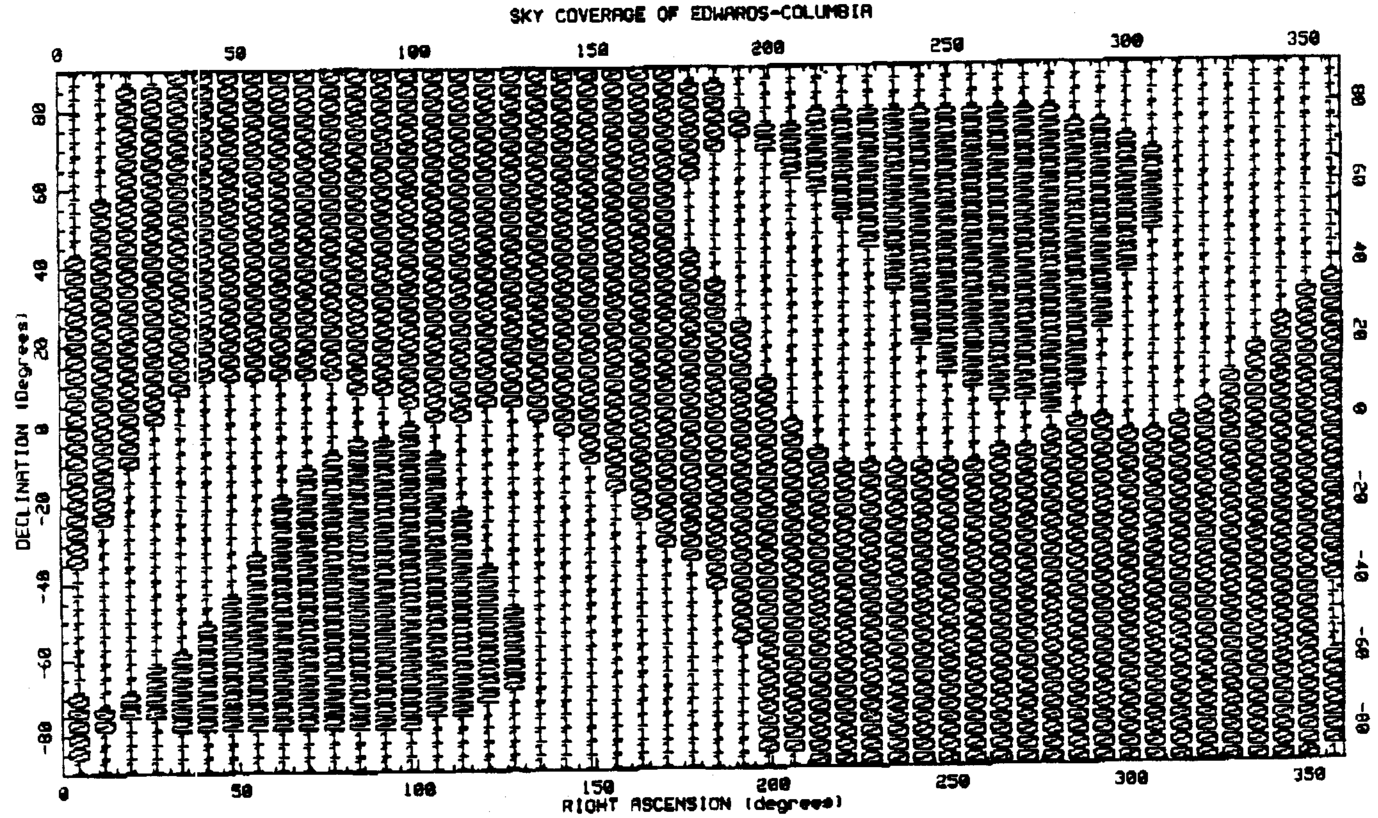
Figure I.2b



SKY COVERAGE OF EDWARDS-COLUMBIA

Number of antennas with sensitivity > 33.00 % of maximum
Averaged over polarization

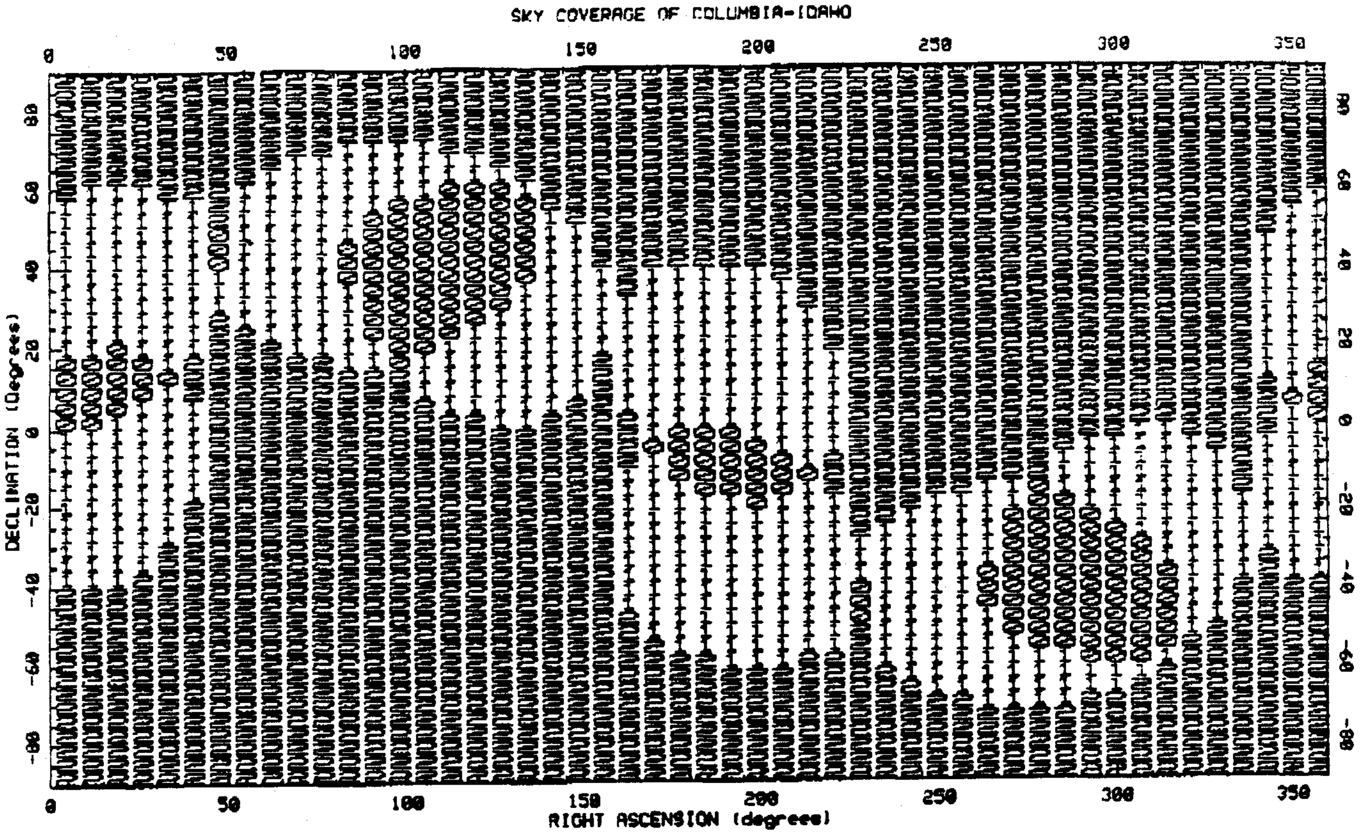
Figure I.3a



SKY COVERAGE OF EDWARDS-COLUMBIA

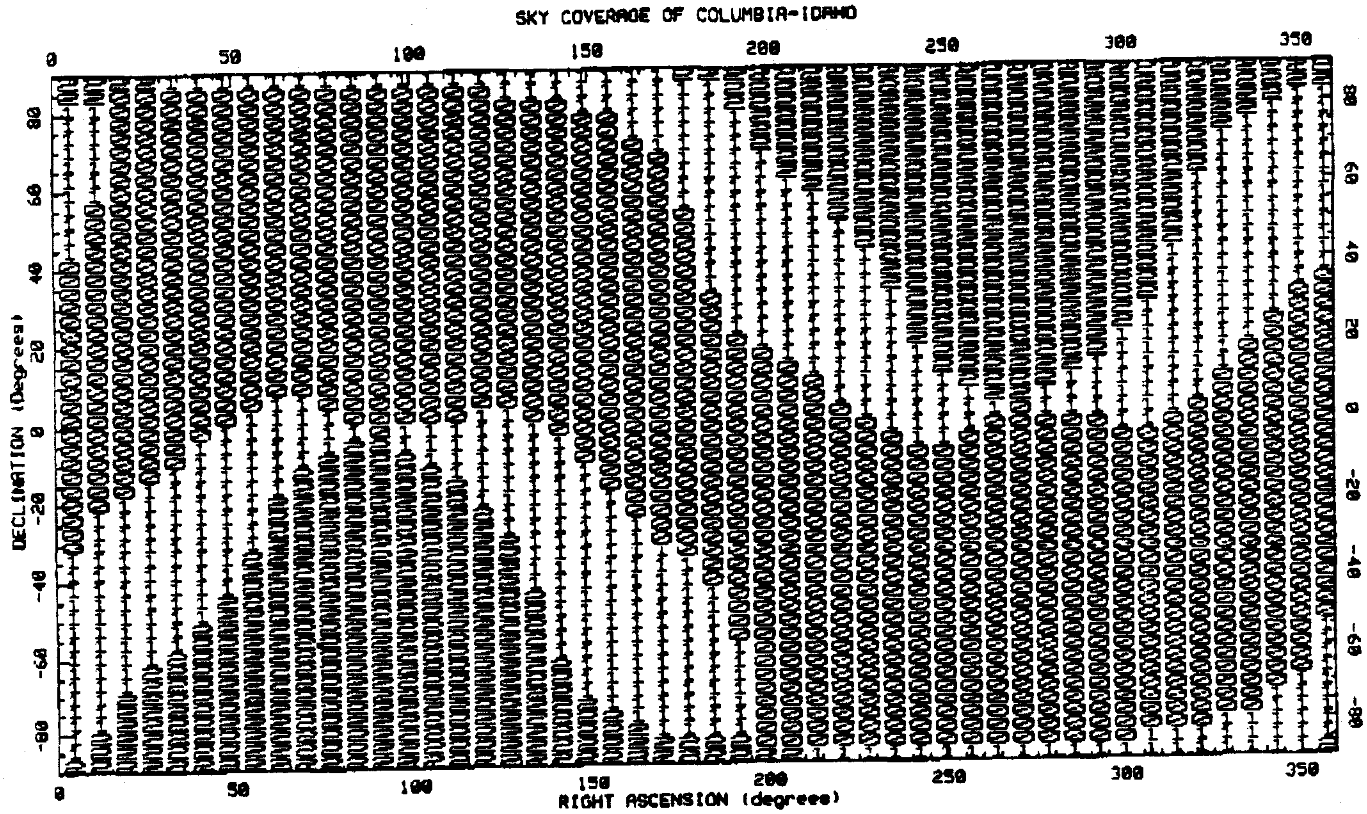
Number of antennas with sensitivity > 50.00 % of maximum
Averaged over polarization

Figure I.3b



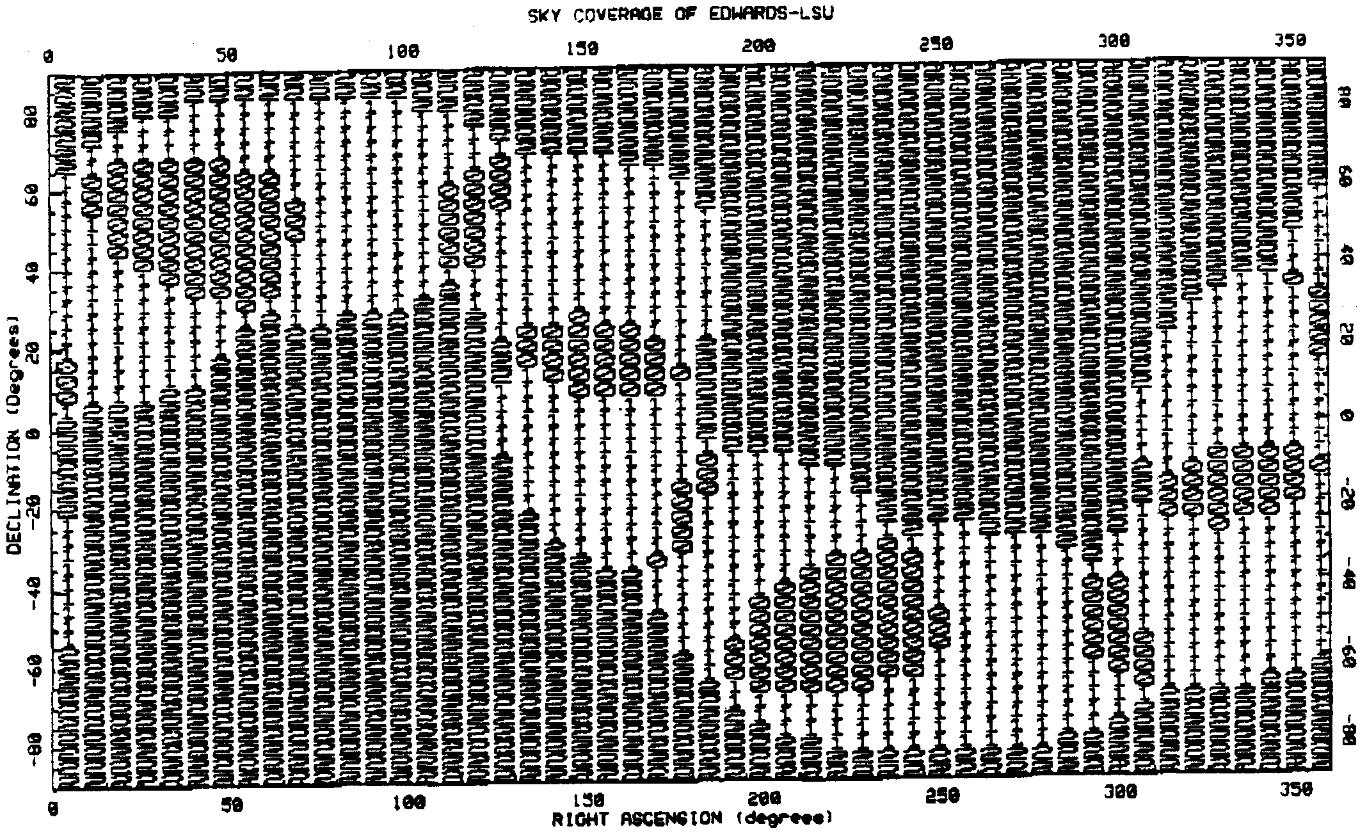
Number of antennas with sensitivity > 33.00 % of maximum
Averaged over polarization

Figure I.4a



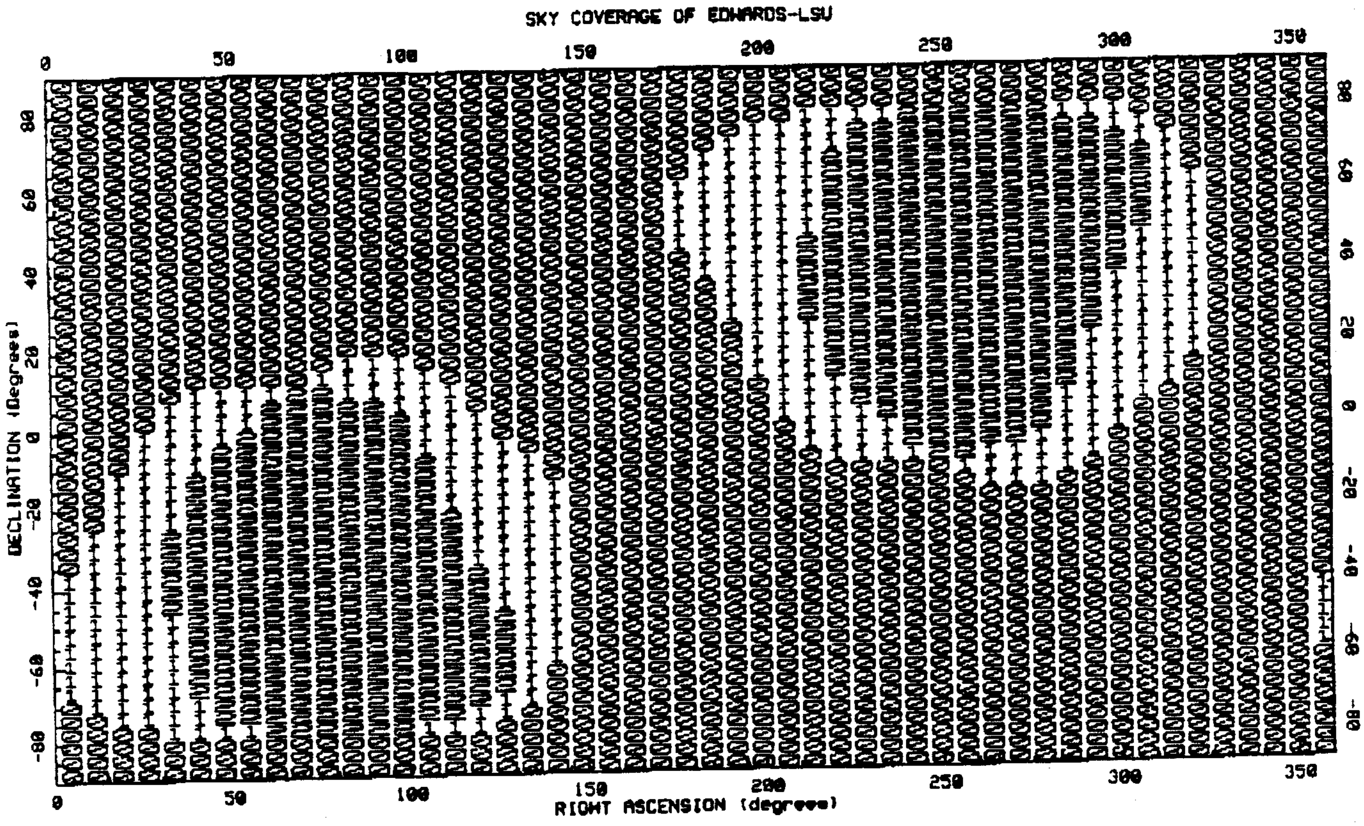
Number of antennas with sensitivity > 50.00 % of maximum
Averaged over polarization

Figure I.4b



Number of antennas with sensitivity > 33.00 % of maximum
Averaged over polarization

Figure I.



Number of antennas with sensitivity > 50.00 % of maximum
Averaged over polarization

Figure I.

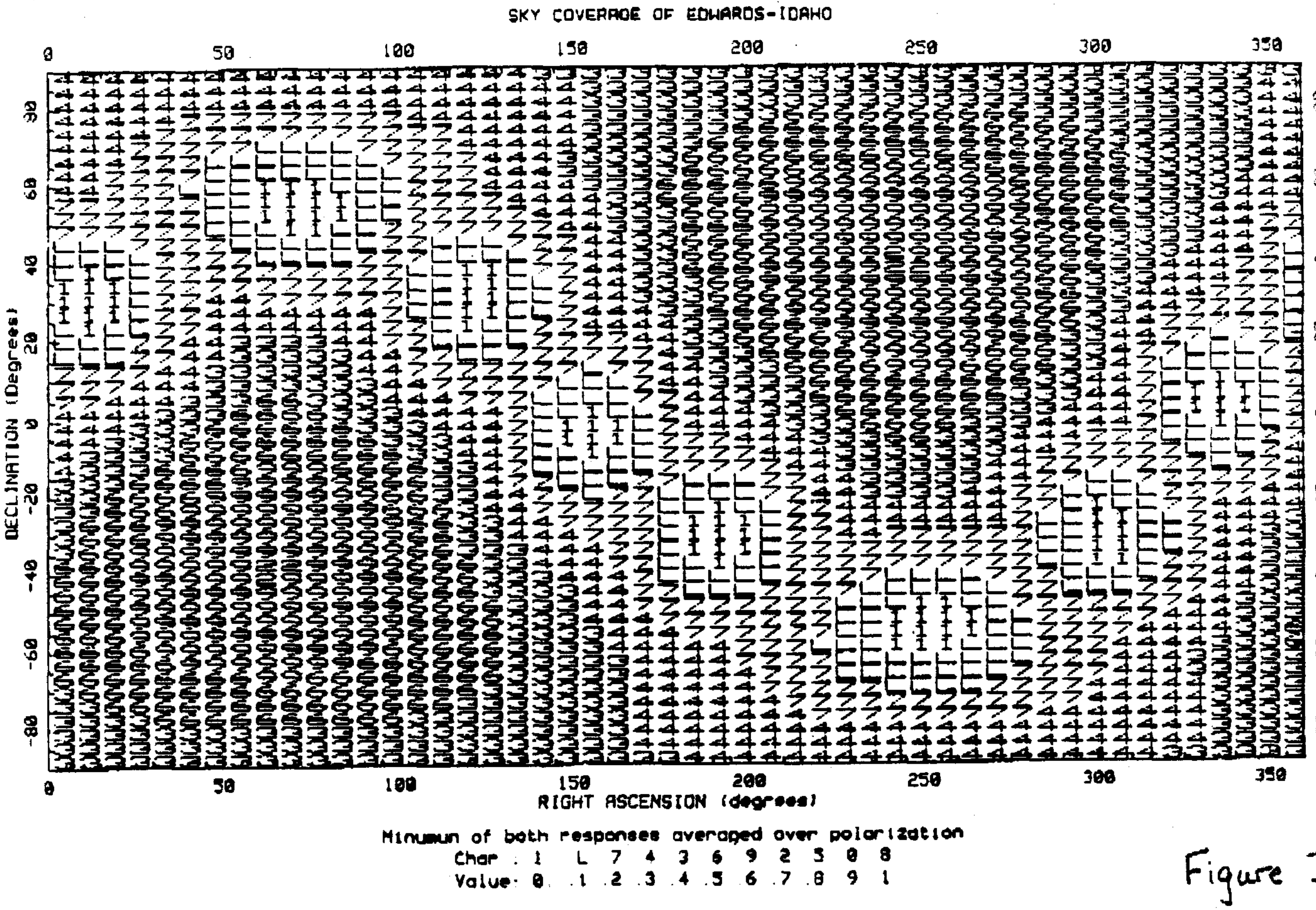


Figure I.6

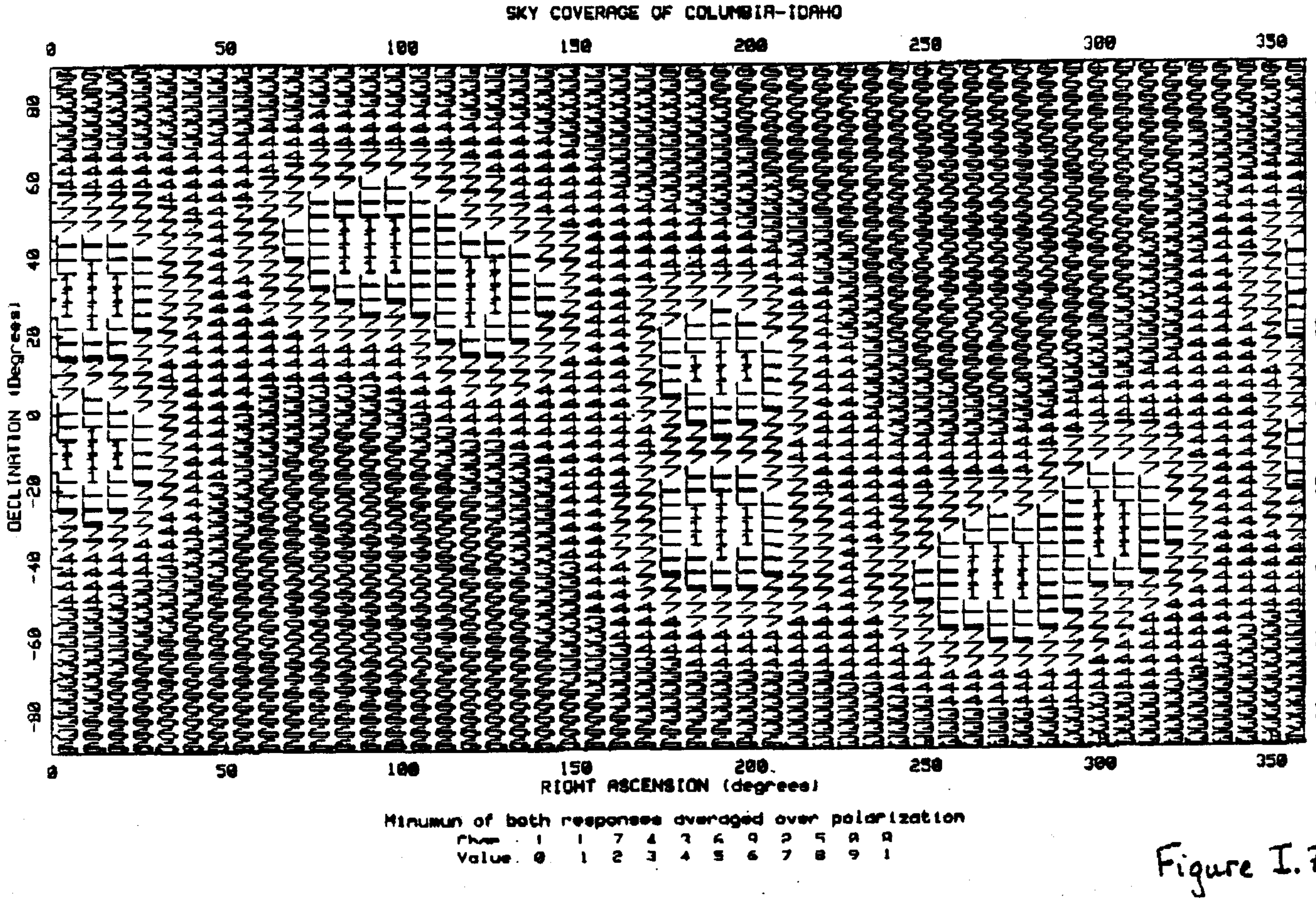
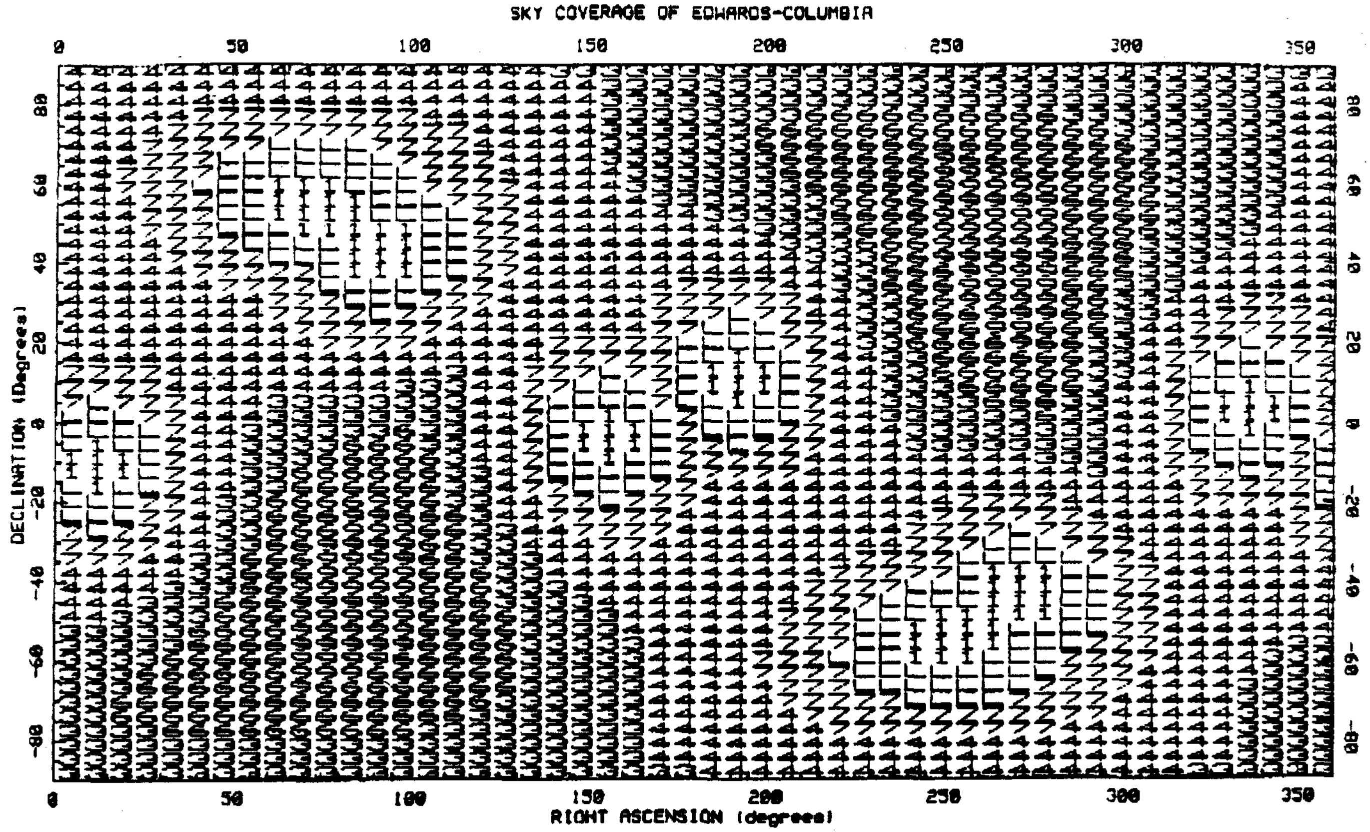
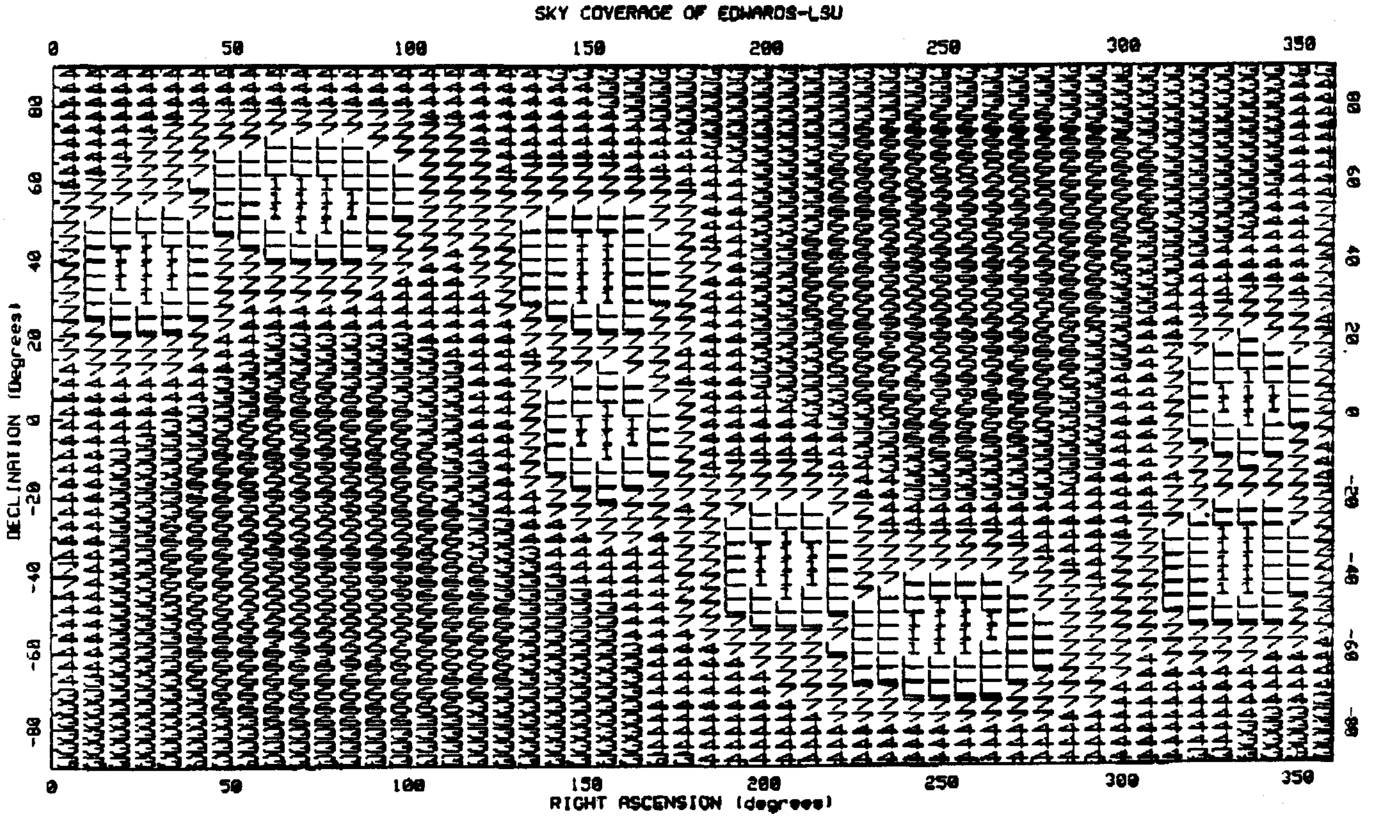


Figure I.7



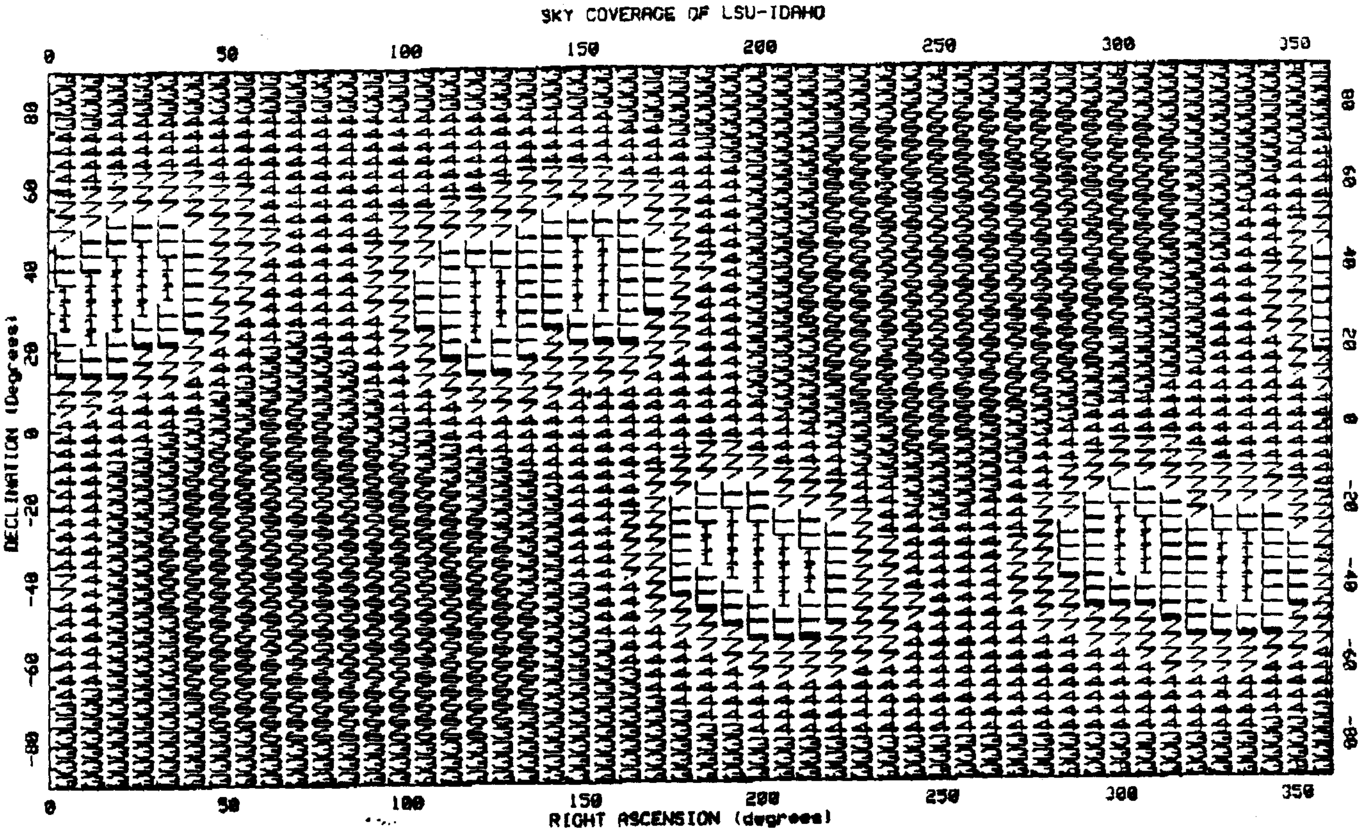
Minumun of both responses averaged over polarization
Char : 1 L 7 4 3 6 9 2 5 0 8
Value: 0. .1 .2 .3 .4 .5 .6 .7 .8 .9 1

Figure I.8



Minumun of both responses averaged over polarization
Char 1 L 7 4 3 6 9 2 5 0 8
Value: 0. .1 .2 .3 .4 .5 .6 .7 .8 .9 1

Figure I.9



Minumun of both responses averaged over polarization
Char : 1 L 7 4 3 6 9 2 5 8 8
Value: 0. .1 .2 .3 .4 .5 .6 .7 .8 .9 1

Figure I.10