Scientific Computer Information Exchange Meeting - May 2-3, 1974.
Statler Hilton, New York City

BNL 18835
Conf-740512--8

A Pattern Recognition Code for Curved Tracks in Cylindrical Spark Chambers*

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ABSTRACT

We describe and evaluate a computer code, PITRACK, which associates sparks into tracks from digitizings produced by a system of nine cylindrical wire spark chambers operating in a 10 kG magnetic field. PITRACK was written in FORTRAN IV and requires 72K octal words of CDC-6600 core storage for execution. Packing and unpacking routines required by the data tape format account for ~ 20% of this core. Track recognition time principally depends on the initial number of tracks to be recognized, N, as

$$t \sim 0.4 + 0.04N^2 \text{(seconds per event)}.$$

PITRACK identifies ~ 94% of all tracks found by a human scanner while ~ 1% of the tracks it found were spurious.

*Work performed under the auspices of the U.S. Atomic Energy Commission

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Introduction

The Multiparticle Argo Spectrometer System, MASS, seen in Figure 1, was capable of recording $\sim 10^4$ inelastic events per hour and recorded 4×10^6 events during its first experiment: proton-proton interactions at 28.5 GeV/c[1]. The analysis of any significant portion of these data required a highly efficient automatic procedure for associating sparks into tracks to form events. Human intervention, by visually scanning events, had to be limited to a relatively small control sample to keep the data processing tractable.

The Vertex Spectrometer[2], VS, of MASS was a system of nine cylindrical wire spark chambers operating in a 10 kG magnetic field. Charged particles produced in an event emerged from a centrally located target, followed helical trajectories, and where they intersected a chamber a spark occurred. The data from each chamber appeared as two independent sets of digitizings. The first set was equivalent to a projection of the helical tracks onto a plane perpendicular to the axis of the helix and resulted in circles. The second set was related to the dip angle of the helical tracks and resulted in straight lines. Combining the two sets of tracks produced a three-dimensional representation of the particle trajectories of an event.

Track Recognition Code

The computer code, PITRACK, was developed to provide track recognition for the VS. The global strategy used in PITRACK was to develop several algorithms which provided a few good initial track candidates. These track candidates would then be upgraded until they either fulfilled most of the conditions for acceptable tracks or failed enough to be rejected. Several intermediate stages of tests and a final track selection determined the ultimately acceptable tracks. Permeating the code was the philosophy that when a track failed a specific test, every effort was made to modify the track until it became acceptable rather than reject it.

We found no single search algorithm which would provide satisfactory track recognition under all circumstances, thus several techniques and multiple searches were employed. The most difficult task was defining for a digital computer precisely what constituted an acceptable track. Again, no single set of conditions was found to exist, so a complex set of rules was developed to include the diverse range of tracks acceptable to human scanners. For example, in many cases it was found necessary to explicitly take into account certain idiosyncracies of the VS chambers and readout system.

Each chamber of the VS produced two sets of digitizings by means of a magnetostrictive readout system. The first set was from the high voltage wires which ran vertically and were parallel to the magnetic field. The second was from the ground wires which were rotated at an angle of $\pm 26.5^{\circ}$ with respect to the vertical, the slope alternating on successive chambers. The high voltage and ground wires were separated by 3/8 inch, with the result that a spark produced two digitizings in different planes, rather than a single point in 3-dimensional space.

The projection of the digitizings from the vertical wires onto the VS median plane, shown in Figure 2, was called the S-view. The rectangle symbolizes the liquid hydrogen target. The beam enters from the bottom, and the magnetic field of 10 kG is directed into the plane of the figure. The nine arcs are the outlines of the cylindrical chambers. The darker points are the S-sparks obtained from the vertical wires. The tracks, as found by PITRACK, are shown along with certain ancillary information. The arc distance to a spark measured along a chamber from the spectrometer center line was called S.

Spark height information was obtained from the slanted wires. It was generated on the set of lines of intersection of the chambers and a cylinder defined by the helical path of the particle and was called the Y-view. Possible spark coordinates occurred whenever a slant wire which fired crossed a vertical wire which also fired. The Y-view of a typical track is shown in Figure 3. The vertical lines represent the chambers and the dark points are the Y-sparks. The circled sparks have previously been associated with another track. The horizontal axis is the S-view arc distance along the track. In the Y-view the track is a straight line. The dark point at the rear of the target is the event vertex.

The Y-view differed from the S-view in two respects. First, the former was not defined until a possible track had been found in the S-view. Second, in contrast to the S-view, not all the coordinates defined by the many intersections corresponded to real sparks. Therefore, tracking was performed first in the S-view. The Y-view was then used to confirm a track candidate and determine its dip angle.

Strategy

An initial event vertex was obtained by projecting the trajectories of external triggering particles back into the VS and intersecting them with the known beam trajectory. For particles detected in the High Momentum Spectrometer (HMS) the digitizings nearest its extrapolated trajectory in the VS were accepted as those from the HMS track. Particles detected in the Low Momentum Spectrometer (LMS) were not similarly treated because of inexactitudes in its trajectory introduced by multiple scattering, energy loss, and LMS spatial resolution.

Five distinct interlocking operations indicated in Figure 4, were performed to extract tracks from the sets of S and Y coordinates.

1. S-view Track Hypothesis

Initial S-spark track candidates were provided by four search techniques. The first, Smooth Track Search, emulated the ability of the human eye to distinguish smooth arcs in a collection of digitizings. The second, Forward Search, found tracks with little curvature which lay close to one another in the forward direction. The third, Brute Force Search, resorted to trial and error to sort out the more complicated tracks. The fourth, 2-spark Search, looked for steeply dipping tracks which exited the chamber volume after passing through only the first two chambers.

Once an S-spark was successfully associated with a track, it was excluded from further initial track searches. However, associated sparks would be used to fill in gaps on other tracks during their development. Typically 5% of all the S-sparks were associated with more than one track.

2. S-view Evaluation

Track evaluation took place at many stages of track development. Before the initial track evaluation, as many sparks as possible were associated with the trial tracks. Chambers were flagged if the track missed or went through an inactive region. The most notable requirement in track evaluation was that trial tracks have a minimum number of S-sparks depending on their configuration.

3. Y-view Tracking

A search was made for trial S-view tracks to find Y-sparks falling along a straight line emanating near the vertex. If no track with a sufficient number of Y-sparks was found, the S-view track was flagged.

Because slant wires alternated in direction from chamber to chamber, the ambiguity created by recording the passage of more than one particle through the chambers was removed. However, reflections due to nearby tracks often occurred on the even or odd numbered chambers. An example of such a track reflection is seen in the upper part of Figure 3 among the circled sparks. Authentic Y-spark associations must therefore include both even and odd numbered chambers.

4. S-view Track Development

The S-spark tracks provided by the initial track searches had many shortcomings. For example, the Smooth Track Search often purposely supplied incomplete tracks. Furthermore incorrect sparks were frequently associated with a track when more than one digitizing existed near the track on a given chamber, or one of the initial searches projected a track incorrectly to a neighboring chamber. These problems stemmed from difficulties such as readout noise, signal inversion, track age, lineup imprecision, delta rays, multiple scattering, nearby tracks, etc. Convergence to the best possible track in the S-view was affected by examining alternative spark combinations. The best track was defined in terms of, first, the number of S-sparks associated with the track and then its chi-squared.

The above type of track development was concerned primarily with the internal consistency of the sparks in a track. Further optimization of the tracks occurred periodically when study was made of how the tracks collectively formed an event. For example, since the vertex was not fixed during tracking whenever it moved significantly an attempt was made to bend tracks to the new vertex by substituting S-sparks on the innermost and outermost chambers, provided this resulted in an improvement in the track quality.

5. Intertrack Comparison

At several stages in the program the established tracks were compared with one another to eliminate spurious ones. These occurred primarily in the forward direction where tracks were abundant, rigid, and closely spaced. Near the VS center line there were dead regions in each chamber which permitted the non-sparking passage of the beam particles. These dead spots introduced distortions and occasional spurious sparking. Thus, for example, forward tracks and tracks which shared sparks in the S-view or the Y-view were carefully scrutinized. In other regions of the chambers the comparison allowed replacement of an occasional incorrect or incomplete track by the correct one.

The location of the vertex was computed after each new track was found by forming a weighted average of track intersections with the beam. The weighting factor was $\sin^2 \theta$ for the Z position and $\cos^2 \theta$ for the X position, where θ was the angle between the track and the beam at their point of intersection. The largest cluster of weighted track intersections was used to compute the event vertex and tracks whose weighted intersections fell outside this cluster were excluded.

After tracking was completed, if there was an IMS trigger, its track was selected from among the tracks identified by the program and flagged. Any of the remaining tracks which passed too far from the final vertex were flagged. These tracks typically resulted from beam halo particles, secondary interactions or decays.

Flexible requirements were an important ingredient in the code. Since the chamber efficiencies had been found to be ~ 95% and independent of the number of tracks[2], a valid track would be expected to have a small number of missing sparks in the S-view. However, before rejecting a trial track with several apparent misses, the S-spark acceptance window was enlarged to allow sparks twice as far from the projected trajectory as normal to be associated with the track, again providing they had no nearby neighboring sparks. Such poorly fitting S-sparks were flagged after tracking was completed.

Another useful technique resulted from the observation that two or more digitizings frequently occurred in near proximity to one another and that these groupings were probably associated with the passage of a single particle. Such S-spark groupings were treated as a unit, although the individual digitizings retained their identity. On the average PITRACK associated 55% of the S-view digitizings into tracks and an additional 15% were indirectly associated by this method. Most of the remaining digitizings are observed in the forward direction and form a non-random background.

Figure 2 is an S-view of an atypical event containing several difficult situations with which this code must contend: a 2-spark track, two side-going tracks with multiple sparks on several chambers, a portion of a chamber where there are no digitizings, tracks which cross one another near the vertex, a possibly ambiguous or spurious track in the forward direction, and several sparks around the dead spaces.

Initial Searches

Four separate searches constituted the Smooth Track Search, each of which began by selecting from two adjacent chambers one S-spark each whose line of connection roughly pointed toward the vertex. A circle was thus defined and used to predict the location of sparks on adjacent chambers. A spark near the predicted location was accepted only if it lay within some angular window. If accepted, the spark was used to calculate a new curvature for the track which then predicted the location of a spark on the next chamber. Each spark of a track was required to have a minimum separation from neighboring sparks on its chamber. If the spark did not meet this separation criterion or if there was no spark in the angular acceptance window, a miss was recorded for that chamber. The search would stop if two consecutive chambers did not provide spark candidates. This procedure often resulted in partial and incomplete tracks which required routines to extend and complete them before they were evaluated.

During the Smooth Track Search the firmness in location of the vertex was continually evaluated. Occasionally for HMS triggers the vertex location had to be stepped through the length of the target until a track with a sufficiently large angle could be found to localize it. If the vertex was found to lie more than one inch outside the physical limits of the target, processing of the event was halted after the Smooth Track Search and the event was flagged.

The Forward Search operated by choosing two previously unassociated S-sparks, one from the first two chambers and the other from the last two. From these sparks a straight line was constructed which was intersected with the remaining chambers. If at least three additional sparks could be found within a window around this line, the track was sent on for development and evaluation.

With the vertex well determined, the Brute Force Search began by taking all the remaining unassociated S-sparks, connecting them two-at-a-time with the vertex to form a circle. If enough sparks were found within a window around the circle, the track was sent on for further work.

The 2-spark Track Search examined pairs of unassociated S-sparks on the first two chambers. Here the only constraint occurred in the Y-view, where it was required that two Y-sparks be found which defined a straight line passing near the vertex. This search increased the effective solid angle of the VS by 20% to 2π sr. Care was exercised to insure that spurious tracks were not introduced by this search.

Evaluation and Performance

PITRACK was written in FORTRAN IV and required 72k octal words of CDC 6600 of core storage for execution. Packing and unpacking routines required by the format of our data tapes accounted for $\sim$ 20% of the core used. Reconstruction time depended on many factors but we found empirically its average approximately depended upon the charge multiplicity of the event, N as

$$t \sim 0.4 + 0.04\ N^2 \text{ (seconds)}$$

(e.g. for a 6-prong 1.8s and for a 10-prong 4.4s). The time to reconstruct individual events, however, varied by a factor of three or more from this average.

The reliability of PITRACK was evaluated by scanning a sample of several hundred HMS trigger events utilizing the interactive graphics program VUE. Initially an event's digitizings were displayed on a video screen with the PITRACK solution superimposed as in Figure 2. The scanner by examining the event in various perspectives, such as the one shown in Figure 5, either verified or improved upon the solution. Interactive operations, using a track ball and teletype, allowed the association of any sparks to make new tracks, and the deletion of associated sparks on all or part of any track.

When VUE was used on the Brookhaven Sigma 7, where it occupied 18k decimal words of core, data to be inspected was stored on a disc file of the CDC 6600. A high speed data link, BROOKNET[3], permitted events to be transferred to the Sigma 7 core at a rate of $\sim$ 200 ms/event when requested by the scanner. After scanning, the event was returned to another CDC 6600 file where it could be retrieved at a later time.

About 94% of the tracks were identified by PITRACK, of which 3% required some improvement, while another 2.5% needed an alteration of flags. Less than 1% of the identified tracks were found to be spurious in the scan. Of the unidentified tracks, a quarter were not acceptable on the basis of the code's predetermined criteria, yet the scanner accepted them on an individual basis. We found that the performance of PITRACK was independent of charge multiplicity up to 8-prongs. For example, in a sample of 6-prong events, 76% had every track identified. Thus, we concluded that there was little correlation among the unidentified tracks.

The performance and yield of the PITRACK search procedures are given in Table I. The Smooth Track Search which was meant to find the easy tracks in fact did identify 70% of all tracks found. In addition its yield was high - more than half the trial tracks it identified were finally accepted. The Brute Force Search, which was left to sort out the more difficult tracks, examined more than twice as many trial tracks as the Smooth Track Search, yet only 9% of those were eventually accepted.

We have thus far processed with PITRACK ~ 600K events recorded by MASS. For these events the VS and PITRACK successfully identified 83% of all charged particles originating from the primary vertex, the remaining 17% were accounted for by particles escaping detection by being produced outside the VS solid angle (~ 9%), in the dead spots of the chambers (~ 1%), by particles of too low a momentum (~ 1%), and by software inefficiencies (~ 6%). Most of these losses can be recovered by requiring charge balance.

Our corrected multiplicity distributions are compared in Table II with bubble chamber data[4] at the same energy, four-momentum transfer and missing mass. Our average charge multiplicity, $\bar{n}_{CH}$, is ~ 5% higher. This systematic deviation is not unexpected since we have not corrected our data for undetected interactions of secondaries, gamma conversions and decays of neutral particles near the primary vertex, charge misidentification of fast tracks, etc. If a 5% excess of tracks is uniformly added to the bubble chamber multiplicity distributions to simulate these effects, the MASS and BC distributions are seen to be consistent.

Conclusions

We have written a pattern recognition program for a digital computer which associates digitizings from a set of nine cylindrical wire spark chambers into helical tracks in 3-dimensional space. The code successfully identifies ~ 94% of all tracks found by a human scanner while ~ 1% of the tracks it finds are spurious. Data taken with MASS and reconstructed by PITRACK are compatible within errors with processed bubble chamber results. We believe that our pioneering efforts in automatic track recognition demonstrates that the large amounts of data from a magnetic multiparticle spectrometer can be correctly and efficiently processed and analyzed.

REFERENCES

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FIGURE CAPTIONS

Fig. 1 Schematic floor layout of the Multiparticle Argo Spectrometer System.

Fig. 2 An atypical event in the Vertex Spectrometer

Fig. 3 Y-view of a typical track. The circled points are reflections of sparks which have been associated with other tracks.

Fig. 4. Logic diagram of the Vertex Spectrometer track recognition code, PITRACK.

Fig. 5. S-view of an 8 prong event in another perspective as displayed by VUE.

Table I. Performance of PITRACK Search Procedure

Search	Identified	Yield
Smooth.Track	70.1%	57.2%
Forward	1.9%	16.5%
Brute Force	27.5%	8.7%
2-spark Track	0.5%	~25%

Table II

<u>Charge Multiplicity Distribution in pp Collisions at 28.5 GeV/c: MASS vs BC</u>

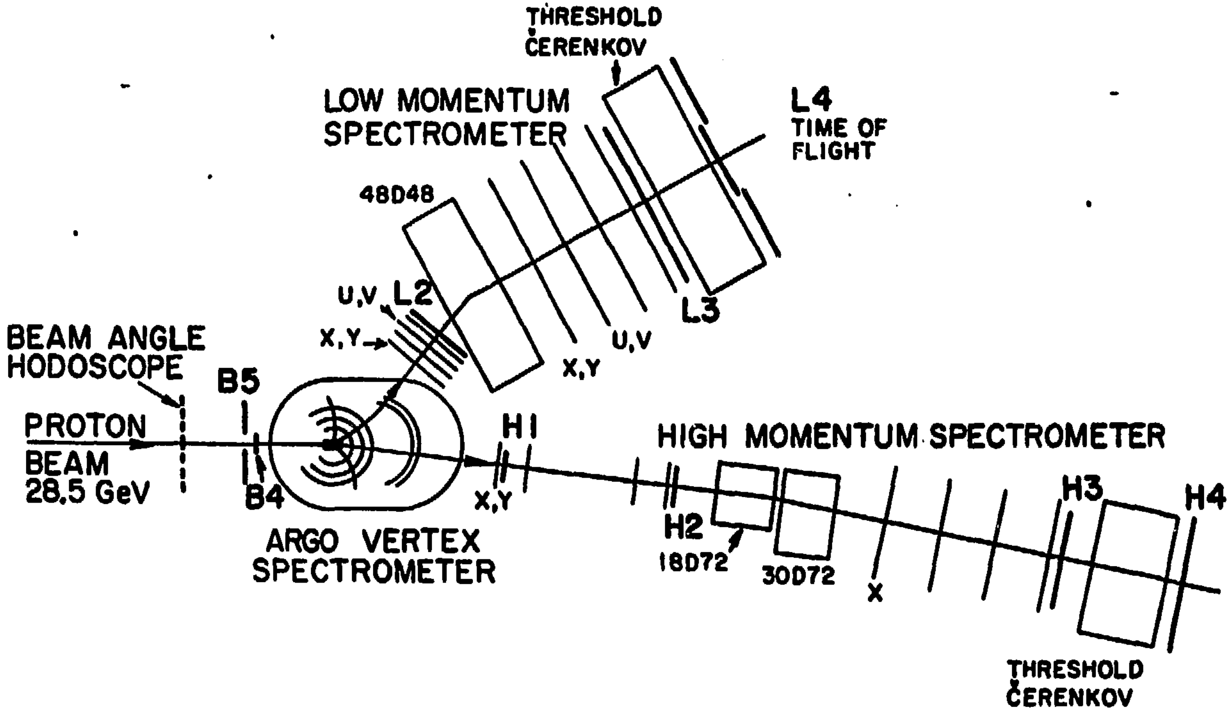
	2 prong	4 prong	6 prong	8 prong	10 prong	$\bar{n}_{CH}$
BC*	30.3% ± .9%	61.7% ± 1.2%	5.9% ± .4%	1.7% ± .2%	.4% ± .1%	3.65 ± .10
MASS†	29.6% ± 1.0%	58.4% ± 1.4%	9.8% ± .6%	1.7% ± .2%	.5% ± .1%	3.83 ± .04
BC + 5%††	27.6% ± .9%	58.9% ± 1.2%	10.8% ± .4%	2.2% ± .2%	.5% ± .1%	

*BC: Recoil proton identified and momentum ≤ 1.3 GeV/c, missing mass to the identified proton between 2.0 and 3.0 GeV.

†MASS: Missing mass to the fast forward proton between 2.0 and 3.0 GeV. The error on $\bar{n}_{CH}$ is statistical only.

††BC + 5%: BC Distribution with a 5% excess of tracks.

Fig. 1



MULTIPARTICLE ARGO SPECTROMETER SYSTEM

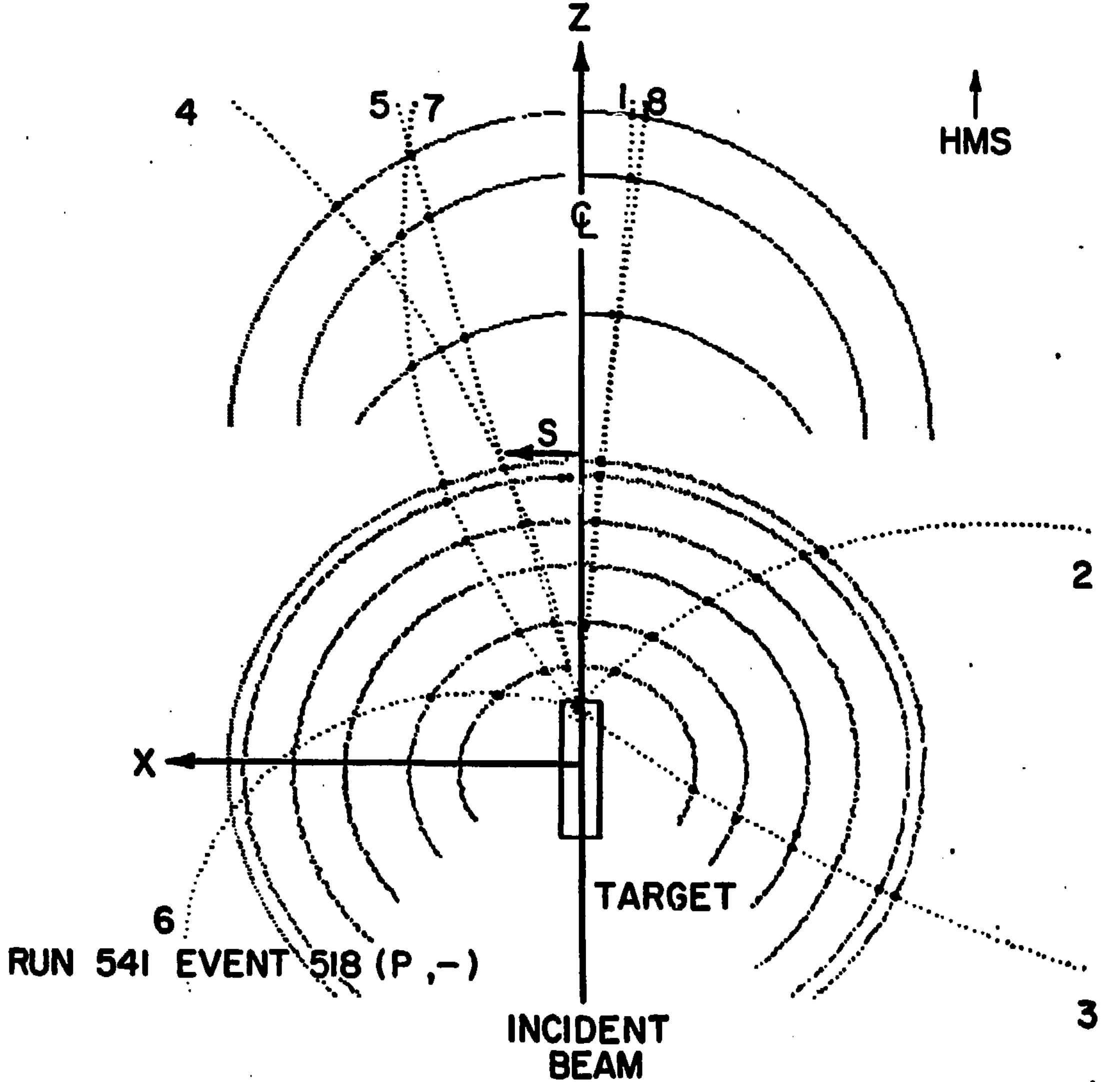


Fig. 2

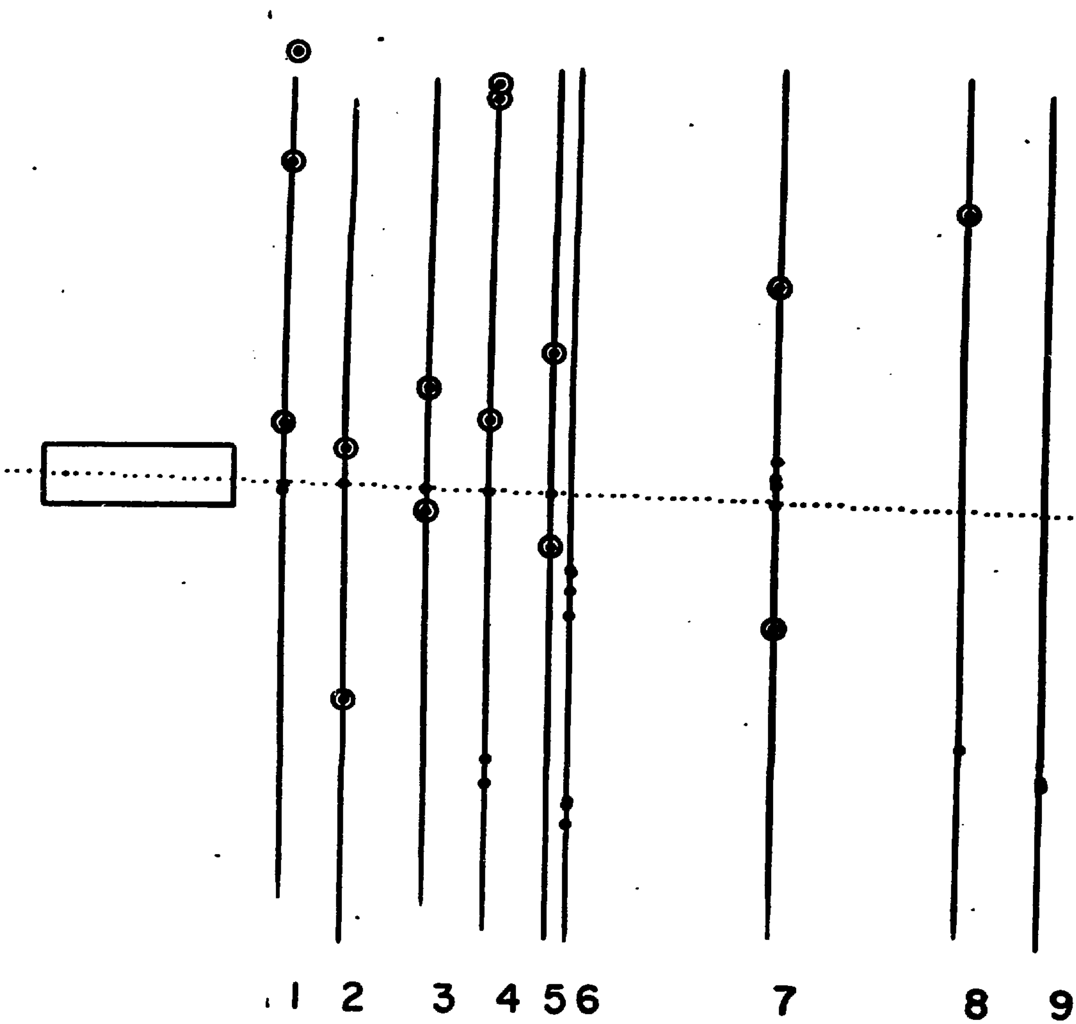


Fig. 3

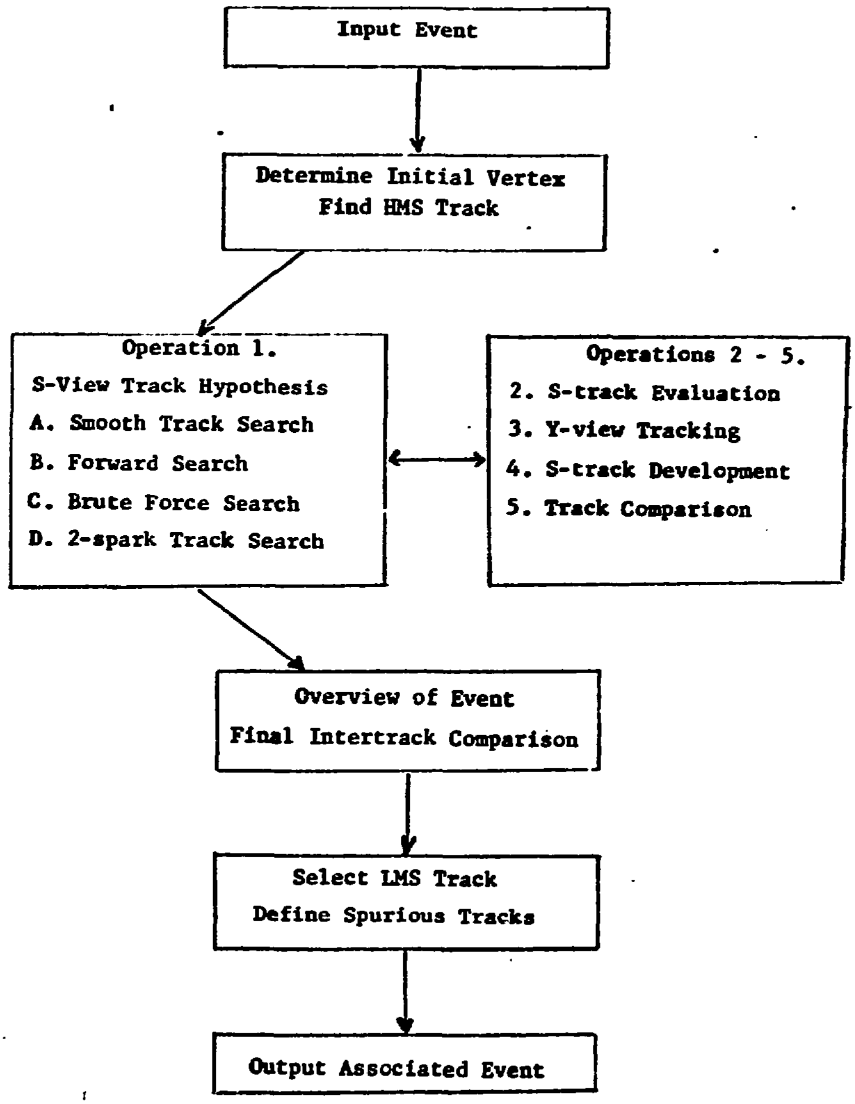

Input Event
Determine Initial Vertex
Find HMS Track
Operation 1.
S-View Track Hypothesis
A. Smooth Track Search
B. Forward Search
C. Brute Force Search
D. 2-spark Track Search
Operations 2 - 5.
2. S-track Evaluation
3. Y-view Tracking
4. S-track Development
5. Track Comparison
Overview of Event
Final Intertrack Comparison
Select LMS Track
Define Spurious Tracks
Output Associated Event

Fig. 4

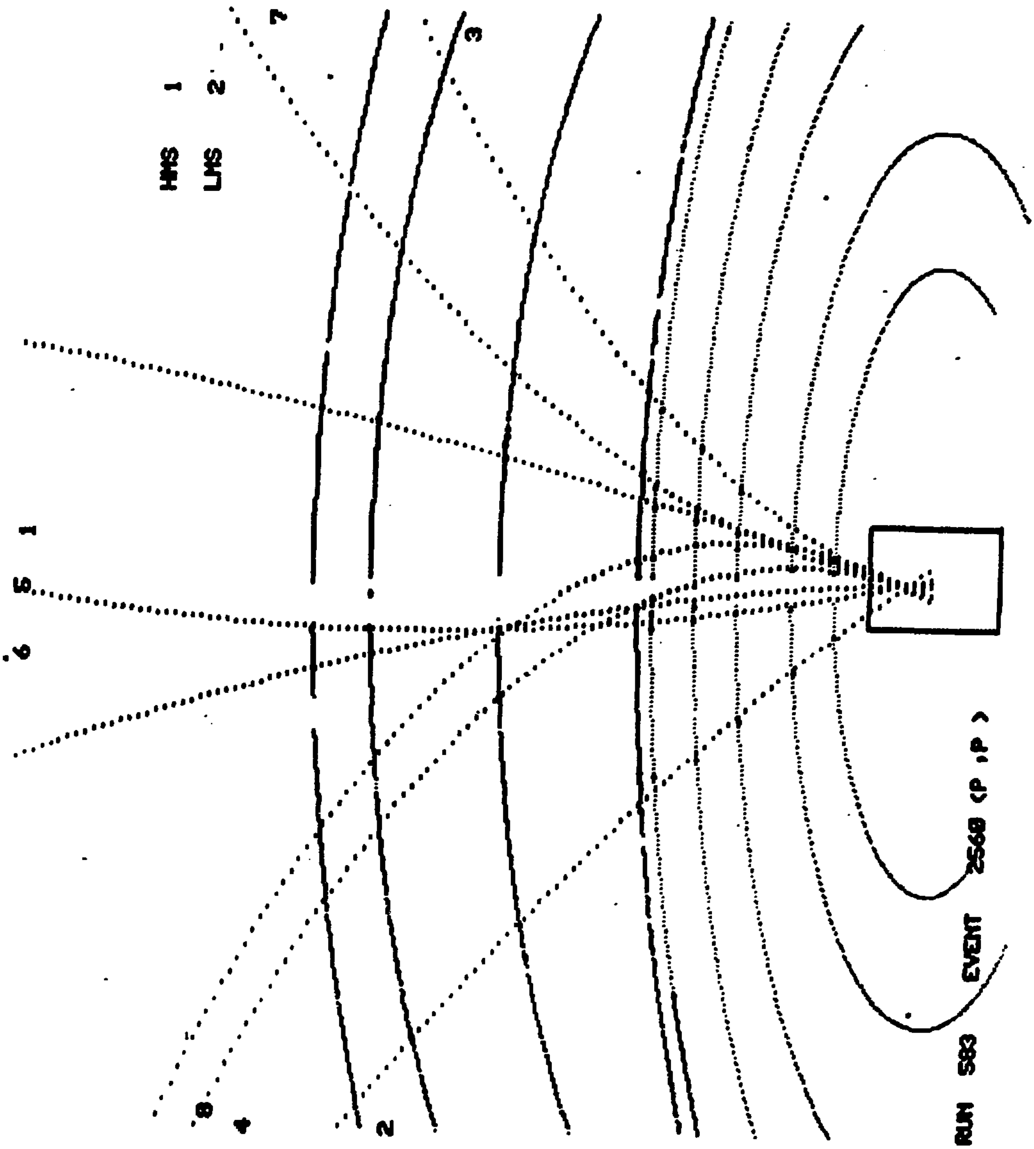


Fig. 5