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NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NATIONAL WEATHER SERVICE
NATIONAL METEOROLOGICAL CENTER

OFFICE NOTE 208

Extraction of the Axi-Symmetric Part of a Hurricane Vortex from High-Frequency Aircraft Observations

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1. Introduction

A key step in the new system[1] built recently to improve the symmetric initialization of the MFM (Movable-area Fine-mesh Model) is the development of axi-symmetric information about the hurricane vortex from ASDL (Aircraft Satellite Data Link) data sets. The problem simply stated is the determination of a radial profile of tangential wind speed and temperature from asynoptic aircraft observations taken every minute over a several hour period for input to the analysis step.

In this note this preprocessing is outlined in detail beginning with raw data and flight plan specifications followed by descriptions of error checking, recoordinization to account for asynopticities, and azimuthal and radial averaging. In addition, criteria are laid out at each stage for the continuation of data processing---only data sets with certain minimal spatial coverage are considered acceptable for spatial averaging. A simplified flow diagram of the entire system is included for reference in Fig. 1.

2. Flight Pattern and Data Coverage

Reconnaisance aircraft are tasked (to the extent possible) to fly the pattern (Flight Plan "A") shown in Fig. 2 when on operational hurricane missions. This so-called double "bowtie" or "butterfly" pattern was adopted as a standard to satisfy minimum vortex-scale data requirements of both the National Hurricane Center (NHC) and the MFM project.

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[1] See Office Note 206 and Preprints, AMS Fourth Conference on Numerical Weather Prediction, Silver Spring, Md., October 29-November 1, 1979 for descriptions of the analysis and dynamic assimilation steps respectively.

If an aircraft completes this mission flying at nearly the same level throughout and the hurricane movement is reasonably well known during the flight period, then it should be possible to accurately determine the symmetric flow at one level at radii (90 to 150 km) appropriate for MFM initialization.

Much of the system design described below was motivated by the dual presumptions that USAF and NOAA pilots would make every effort possible to satisfy these requirements, but that frequently they would fail for one reason or another. Criteria for useability are based on a strong desire to exploit a flight but are tempered by an equally strong desire to avoid symmetric estimates based on biased sampling.

Experience with research ASDL sets where Flight Plan "A" was not necessarily required or even desirable has shown that half of the time (three out of six cases) the compromises adopted produced symmetric information for the analysis step. However, in preliminary tests two out of the three inadequate aircraft sets were successfully augmented with satellite cloud-tracked winds obtained with a shorter picture interval that may be used operationally. Based on thse considerations it appears that operational reliability for this system is realizable.

In the event of failure two additional levels of backup are designed into the system that will provide a reasonable if not as precise input to the analysis step. These will be described later.

3. Data Composition and Flow

The actual data consists of one-minute averages available every minute of time, latitude, longitude, pressure altitude (standard atmosphere height of observed pressure), D-value, wind direction and speed, temperature, and dewpoint.

The data is stored on the aircraft and relayed via satellite[2] every half hour to the National Meteorological Center (NMC), where it is stored in NWS.NMC.PROD.RAWDTA.ASDALD.[3]

This file is in turn searched for current flights which are sorted into up to four different files representing four different missions. During this sorting garbled data are tossed or flagged with 9999999 and individual observations are stored as numbered card images in 8I9 format for subsequent TSO editing or input to graphics or analysis routines. No physical conversions or error checks are performed at this time. After subjective TSO and graphics review each flight is automatically processed separately to produce independent inputs from different levels to the analysis step. During the man-interactive step the options to blend two flights near the same level or blend a satellite set with an aircraft set can be selected as well. Prior to processing each flight boundary conditions for the axi-symmetric model are determined from the current FOO and GES files, three storm positions and times and a backup tangential wind estimate obtained from NHC are read, and an ensemble mean storm with auto-and cross-correlation fields (see O.N. 206) is determined. The hurricane's position with time is represented parametrically by fitting latitude and longitude separately to a second-degree polynomial in time.

Only one pass is made through each card-image data file prior to azimuthal averaging. A datum is accumulated in its appropriate storage location in an array representing a cylindrical-height frame. This array has 40 radial

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[2] See National Hurricane Operations Plan. FCM 79-2, Washington, DC, May 1979.

[3] The catalog for this file is record ASDCTL in NWS.NMC.PROD.RAWDTA.RAWCTLS.

locations (representing 7.5 km radial increments from 0 to 300 km radius), 36 azimuthal locations (representing 10 degree azimuthal increments) and three vertical locations (representing > 800 mb layer, 800-600 mb layer, and < 600 mb layer).

Thus a storm volume 300 km in radius is cylindrically divided into 4320 subvolumes. Seven such arrays are necessary to integrate potential temperature and accompanying sigma and number of observations, as well as tangential and radial wind components and accompanying sigma and number of observations. The 7.5 km radial increment is a convenient integer divisor of the axi-symmetric model's grid size of 60 km as well as typical of the distance existing reconnaisance planes can travel in the sampling period of one minute. Error checks and recoordinizations performed on each observation as it is read are described next.

4. Data Editing and Conversions

The first of a series of data checks is designed to skip over observations with critical elements missing: If any one of time, latitude, longitude, pressure altitude, and D-value is missing or if both wind speed and direction (packed as one group) and temperature groups are missing the observation is unuseable.

These checks are followed by gross error checks in which the five position groups alluded to above (time, latitude, etc.) and the wind and temperature groups are checked for being within range (e.g. $0 \leq$ time ≤ 2400) or reasonable (e.g. $|$D-value$| \leq 3000$ ft.) whichever is appropriate. Groups that fail these tests are flagged with 9999999 when necessary and the criteria for retention used in the previous step applied. Thus at this stage observations with both or either wind speed and direction and temperature groups might be retained.

After this initial editing latitude and longitude are converted to decimal numbers and the latter converted to east longitude, and time is converted to a real number scale where the appropriate synoptic time is set to zero. The elapsed time and the great circle distance from the previous observation are computed. If the elapsed time is zero the observation is tossed, otherwise a speed is computed and tested against realistic aircraft speed bounds (i.e. 25 m/sec $\leq$ speed $\leq$ 200 m/sec). Observations that fail this test are tossed and the next observation checked is tested against the last retained observation.

These checks begin with the second observation that survives the gross error checks and no data is tossed until at least one consistent pair has been identified. This last precaution prevents a whole record of data from being rejected based on a bad first observation. Naturally, several situations can lead to retention of incorrect observations or rejection of good observations (e.g. when the aircraft loops sharply the speed will be seriously underestimated and may fall below the lower bound). But for the most part the speed check has proved to be a powerful filter for the data set, frequently rejecting observations with subtle errors in one or more digits that passed the other tests. For a satellite set the procedures in the last two paragraphs are bypassed.

Upon successful completion of error testing an observation is ready for transformation to a lagrangian, polar-sigma cylindrical coordinate system moving with the storm center. In this manner a major correction to account for the asynopticity of the data is made. Additionally, a correction is made to the wind to take into account the large asymmetry implied by storm translation. This latter correction has no effect on the subsequent azimuthal averaging when data coverage is thorough, but will prevent a serious bias from entering estimates in marginal coverage situations.

Before these adjustments are made to the observation, pressure, height, the u- and v-componets of the wind, and potential temperature are computed. Next the storm position at the observation time is calculated. Once this is available both the great circle distance from the storm to the aircraft and the azimuth of the aircraft from the storm measured in the tangent plane through the storm center can be determined. These steps and those in the next two paragraphs are illustrated In Fig. 3.

Knowledge of the great circle distance and pressure also permits the determination of an appropriate sigma-level for the observation on the axi-symmetric model domain. This is acccomplished by interpolations from the ensemble mean storm gridded sigma-pressure fields. At this point enough information is available to assign an observation to a specific location in the accumulation arrays.

Before doing so however the winds must be resolved into radial and tangential compoenets and adjusted for storm motion. This is done by first finding the azimuth of the storm from the aircraft measured in the tangent plane through the aircraft and also by computing the instantaneous storm velocity. Both velocities are then transformed into their local radial and tangential components and the storm's velocity is subtracted from the wind's component by component. The resulting wind components, potential temperature and sigmas are then added to the contents of the appropriate locations in the accumulation arrays and counters incremented by one. Data falling outside of 300 km from the storm's center are of course not accumulated.

After all observations from a flight have been processed two checks are made: (1) If no data was accumulated subsequent steps are skipped and processing of the next flight begins, and (2) if a satellite wind set or second flight set is to be blended with the first further processing is postponed til the second set has been accumulated.

Plots of ASDL data sets for Greta on Sept. 17, 1978 and Ella on Sept. 3, 1978 before and after recoordinization are shown in Fig. 4. In both cases the storms were moving at moderate speeds. Near the centers horizontal shears are large and the sensitivity to small errors in position is large. However, away from the center, at radii of interest to this initializatlon problem, the "snapshot" plots present a consistent and reasonable picture of the flow around the storm.

The extent to which these coordinate transformations are successful depends principally on three factors: (1) The accuracy of the specified storm motion, (2) the speed of the storm, and (3) the rate of change of the storm (intensity changes, asymmetry rotation, etc.).

Their impact is minimized and decreases rapidly outward from the storm center when sufficient space and time data coverage is followed by suitable smoothing. Here the accumulation process combined with azimuthal averaging described in the next section functions as both time and space smoothers, while the corrections for storm motion and the monitoring of azimuthal data distribution also described later reduce the procedure's vulnerability to sampling biases with respect to major asymmetries. Adequate data coverage will be ensured by enforcement of aircraft mission requirements, and augmentation of aircraft winds by satellite sets.

Finally, it should be noted that all of the data available to this analysis will also be available in plotted form to NHC tracking experts who ultimately supply the information on which the storm motion is based.

Thus it is unlikely that input storm movement will often adversly impact data recoordinization.

5. Azimuthal and Radial Averaging

After all data has been recoordinatized and accumulated, potential temperature, the two wind components, and accompanying sigmas in each of the three layers and each 7.5 km annulus into which the data was partitioned are separately azimuthally averaged. At the end of each operation a determination is made whether continued processing is justified.

First, the summed data in every ten-degree section of an annulus that contains a sum is divided by the number of observations in the sum to obtain an average for the annulus section. At the same time a count is made of nonempty annulus sections and their index range over the annulus is noted. If there are less than three full sections the annulus is flagged as empty and the processing summarily moves to the next annulus (variable/level).

If there are three or more full sections the annulus is considered full if any three of these sections are distributed azimuthally such that consecutive sections are no closer together than 90 degrees but no further apart then 150 degrees.

When two consecutive sections satisfy the criteria but a third section cannot be found to complete the triad, this implies that a certain zone of adjacent empty sections exists in the annulus. If a full section can be found in each of the zones delineated by the boundaries of the empty zone and radial lines half the angular distance towards the first two full sections, then the annulus is also considered full. An example is given for clarity in Fig. 5.

If no three or four full sections can be found that pass these tests the annulus is flagged as empty no matter how many full sections it contains. This is because the observations are poorly distributed azimuthally and a representative azimuthal average can probably not be inferred for the annulus.

After an annulus has been flagged as full, azimuthal averaging is performed. Every empty section in the annulus is assigned a value through linear interpolation between full sections. All thirty-six section values are then summed and averaged. In the last operations the previous corrections for storm motion play a vital role in preventing serious over- and under-estimates of the tangential wind speed in those cases where interpolations must be made over wide azimuthal ranges.

Subsequent to azimuthal averaging partial radia-sigma profiles are available for further analysis. Before radial averaging is performed the radial range of the partial profile is noted and at radii within this range where empty annuli are flagged azimuthally averaged values are provided by linear interpolation from full annulus radii.

The resulting patched-up profile may then be rejected from further consideration if it is either too narrow in radial extent for subsequent smoothing (less than eight 7.5-km radial increments) or does not extend to a large enough radius (120 km for the wind components and 180 km for potential temperature). If the wind profiles at a particular level are rejected so is the temperature profile but not vice versa.

Examples of reconnaisance data that either failed or passed these tests are shown in Figs. 4 and 6. In the Greta case in Fig. 4c and the Ella case in Fig. 6a the storm was sampled by the aircraft in all quadrants over a large radial extent. For the Ella case in Fig. 4a the northern quadrants were sampled at only a few radii and the profile width criterion was not met. In contrast, the sampling of Anita shown in Fig. 6b was quite adequate out to 80 km or so from the center but unsatisfactory beyond that in the north and south mission tracks. Not illustrated in Fig. 6b is the fact that the aircraft flew its approach leg at a considerably higher altitude than its penetration legs.

The final step before data is picked off the profiles for analysis consists of passing an eight-point moving average over the profile in an attempt to approximately scale the input to that appropriate for the model/analysis system, i.e. 60-km resolution. Data in eight adjacent radial sections are averaged and the result is assigned to the radial point between the fourth and fifth sections, i.e. points at 30 km, 37.5 km, 45 km etc. Unsmoothed and smoothed tangential wind profiles are presented in Fig. 7 for one of the thorough-coverage flights described above and shown in Fig. 4d.

6. <u>Data Assignment and Extrapolation</u>

Once a radial profile for any particular flight level set or combination of flight-flight or satellite-flight sets is available data can be read off it for direct insertion into the radial-sigma domain analysis routine. The assignments are made at several radii that match radii of grid points in the axi-symmetric model equal to or greater than 150 km. This cutoff radius is based on scale considerations and should of course be decreased (along with the smoothing window described in the previous section) as model resolution is increased.

The assignment is straight forward for temperature and for the tangential wind speed when their respective profiles extend to or beyond a grid radius: Appropriate values for the grid point radius along with accompanying sigmas are picked directly from the profiles.

However, when a point falls outside of the range of the profile, under certain conditions, the tangential wind will be extrapolated to the point. This occurs when the profile extends to within 60 km of the grid point at 150 km or to within 30 km of the points at 210 km and 270 km. The extrapolation makes use of the power law

$$c = vr^{-x}$$

where c is a constant, v the tangential wind speed, and r the radius. Observational studies suggest values of x between 0.5 and 1.0. For the time being x is set here at 0.75, and represents a compromise based on these observational studies and current experience. The extrapolation was necessary for the case shown in Fig. 7 where it is indicated.

When all flights and levels have been processed the resulting data set is then subjected to the absolute value and consistency checks described in O.N. 206 and, if not completely rejected, analyzed by the method also detailed in the note.

6. Backup and Default Inputs to Analysis in the Event the ASDL System Fails to Produce Data

In the event the ASDL system fails to produce data suitable for analysis in the axi-symmetric plane, a backup and default have been designed into the system that should produce reasonable results.

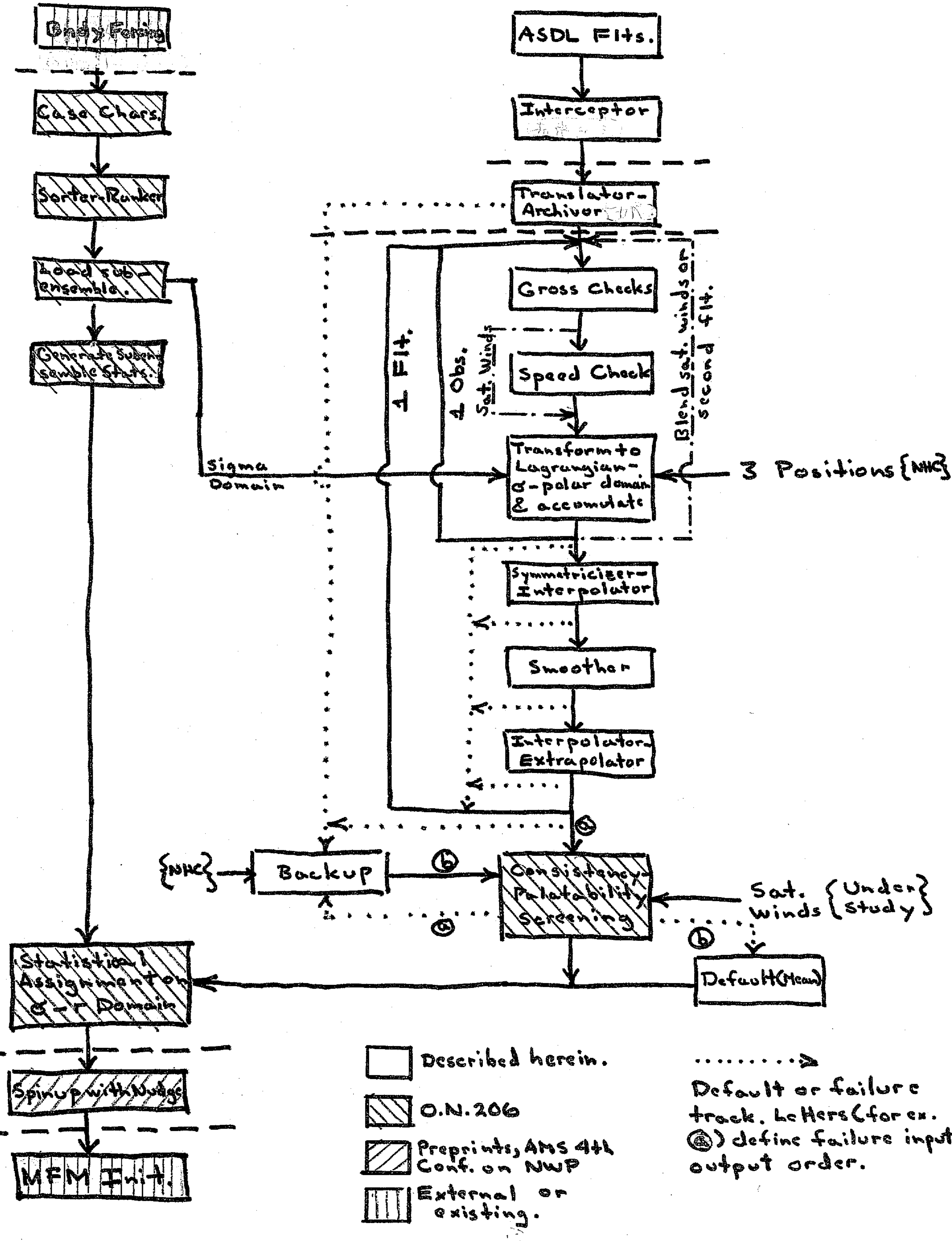
The first of these is a subjective estimate of the azimuthally-averaged tangential wind speed at some pressure and some radius outside that of the maximum wind arrived at jointly by NHC and Miami Satellite Field Service Site experts and communicated to the NMC Senior Duty Meteorologist. He in turn inputs the information before ASDL processing begins at the same time he enters the storm positions required in other steps.

Frequently these subjective estimates will be based on reconnaisance data that was rejected for objective processing. This wind is then extrapolated to the 150 km radius by the power law described in the last section.

If the backup input fails the tests alluded to in O.N. 206 then a default analysis is used that essentially reproduces the ensemble mean storm appropriate for that day's large-scale environment.

A desirable goal is to increase the frequency of successful objective ASDL exploitation. The judicious blending of 15-min satellite cloud-tracked winds with a reconnaisance mission appears promising in this regard. In the current system this option is feasible, but vertical separation of data sets is accounted for very crudely. Several ideas for the treatment of this problem and other data inhomogeneities such as asynopticity, scale, and error, as well as the three-dimensional analysis problem, will be discussed in a forthcoming note that is in preparation.

Figure 1


Bndy Forcing
Case Chars.
Sorter-Ranker
Load sub-ensemble.
Generate Subensemble Stats.
ASDL Flts.
Interceptor
Translator-Archiver
Gross Checks
Speed Check
Sat. Winds
1 Obs.
1 Flt.
Blend sat. winds or second flt.
Sigma Domain
Transform to Lagrangian-σ-polar domain & accumulate
3 Positions {NHC}
Symmetricizer-Interpolator
Smoother
Interpolator-Extrapolator
a
{NHC}
Backup
b
a
Consistency-Palatability Screening
Sat. winds {Under study}
b
Default (Mean)
Statistical Assignment on σ-r Domain
Spinup with Nudge
MFM Init.
Described herein.
O.N. 206
Preprints, AMS 4th Conf. on NWP
External or existing.
Default or failure track. Letters (for ex. ⓐ) define failure input/output order.

From: National Hurricane Operations Plan
FCM 79-2
May 1979
CHAPTER 4
APPENDIX A
ATTACHMENT 1A

RECOMMENDED PATTERN "A" EXECUTION

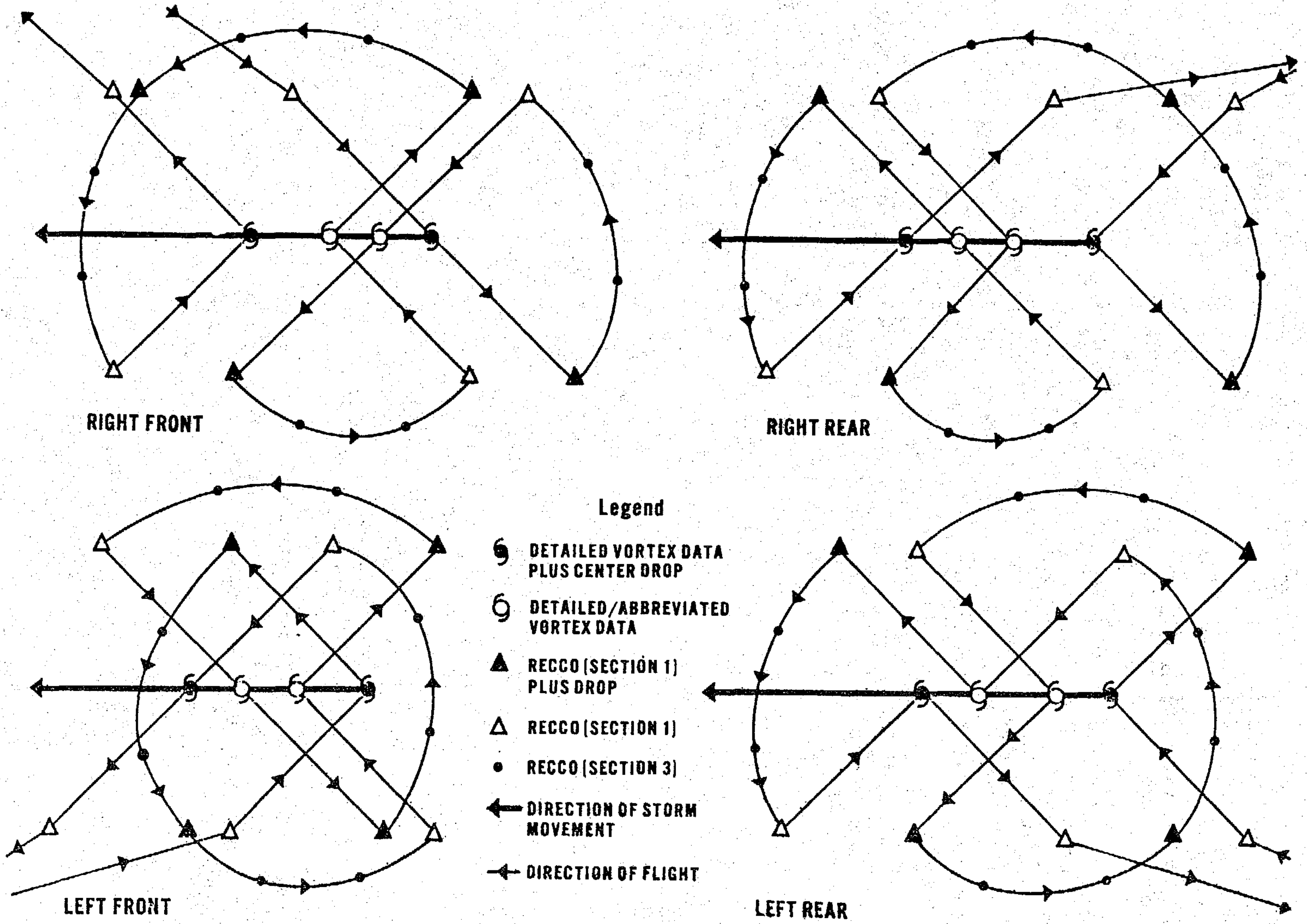
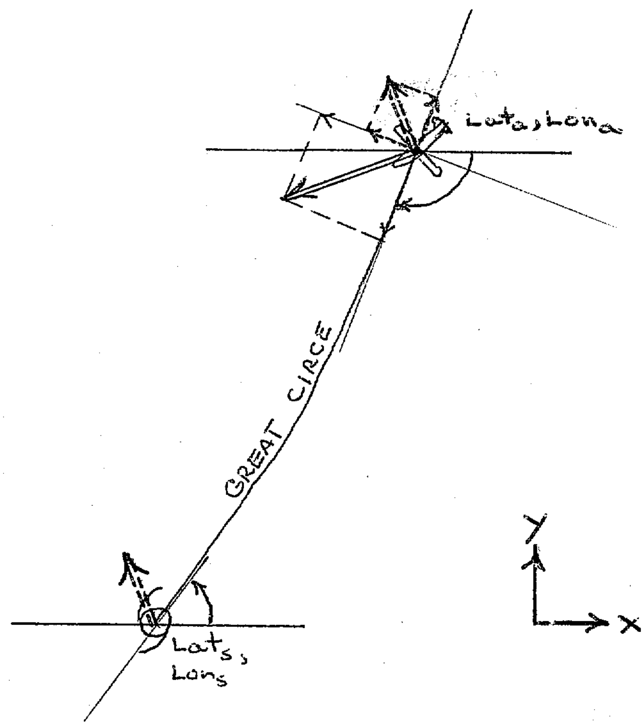


Figure 2

Figure 3



Storm Lat: $y = a_y + b_y t + c_y t^2$

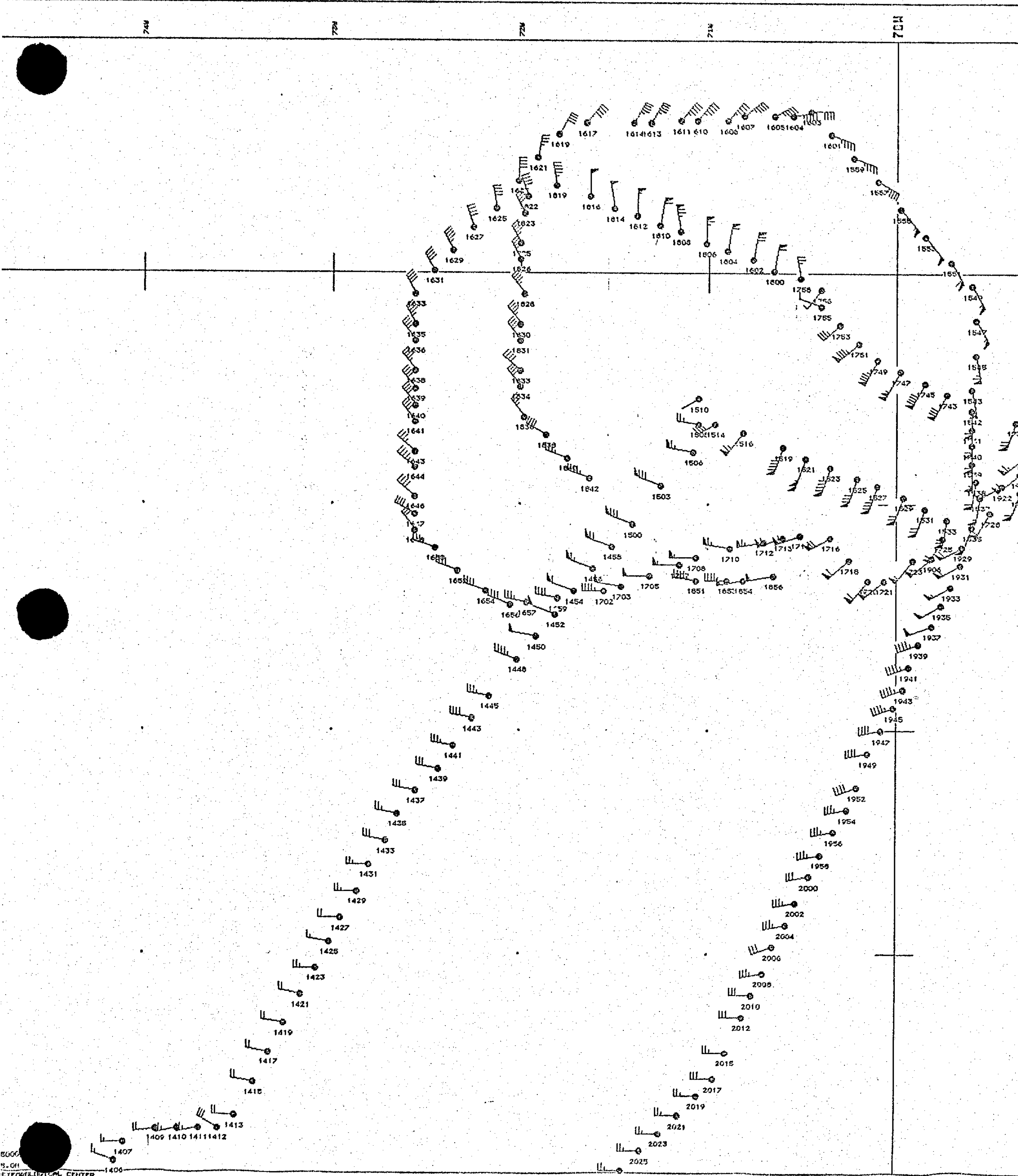
Storm Lon: $x = a_x + b_x t + c_x t^2$

$$\dot{y} = b_y + 2 c_y t$$

$$\dot{x} = b_x + 2 c_x t$$

Unshifted

Fig. 4a



9 3 78 MFM/ASDL DATA PLOT TEST LIVEZEY BIN 02 PLEASE

ELLA

Before Recoordinization

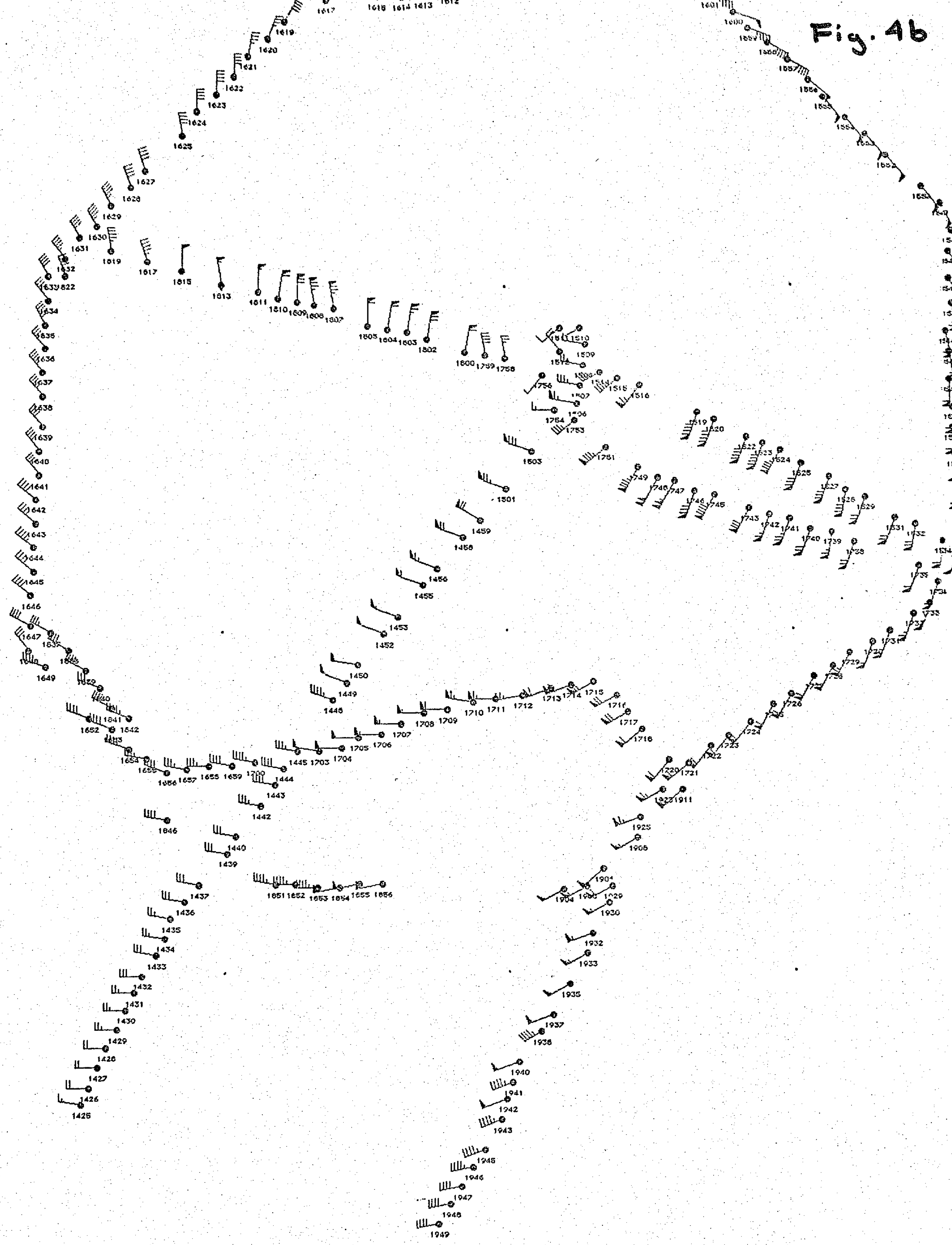


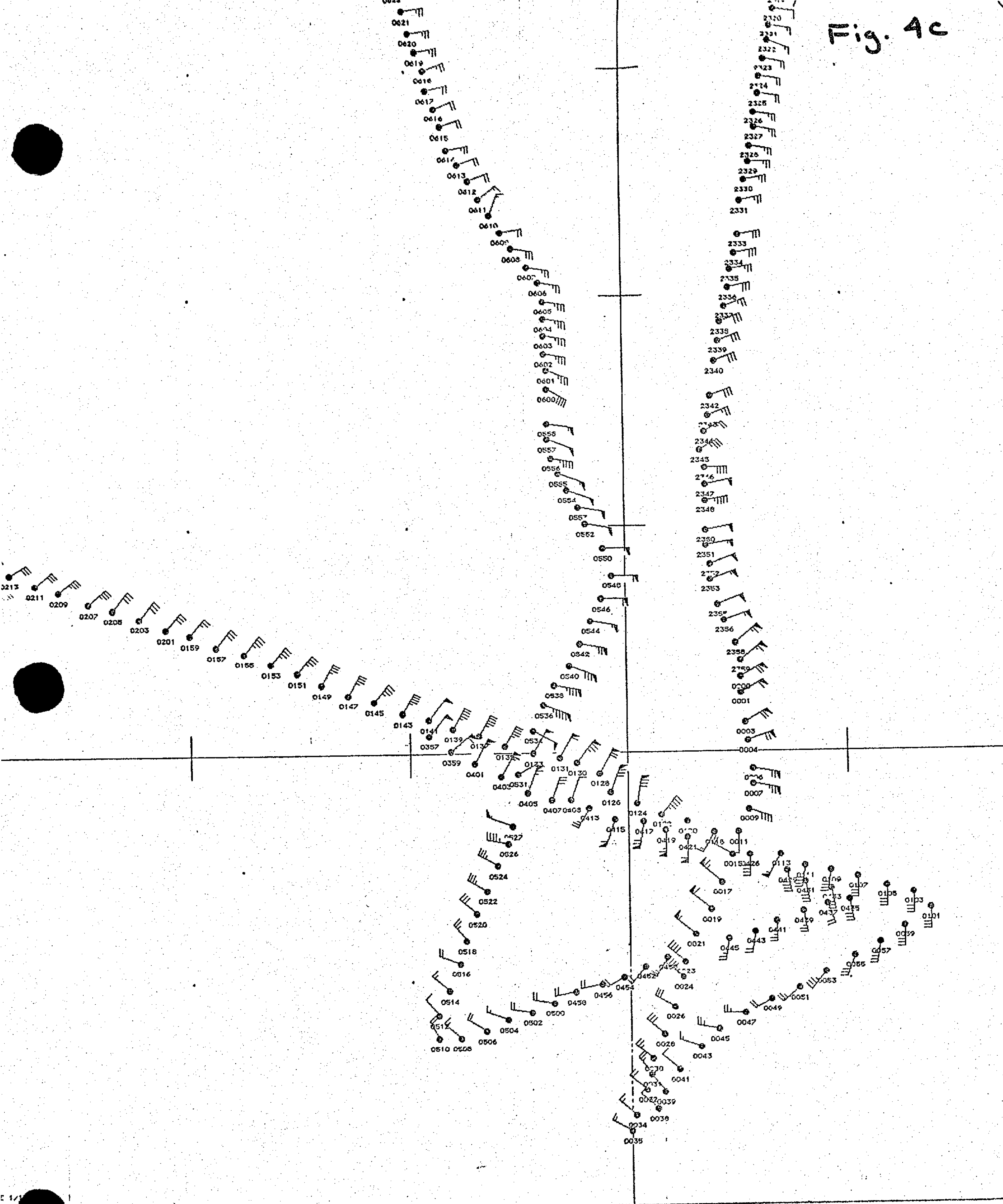
Fig. 4b

SCALE 1/1000000
TRUE AT 30.0N
NATIONAL METEOROLOGICAL CENTER

ASDL 9 3 78 MFM/ASDL DATA PLOT TEST LIVEZEY BIN 02 PLEASE
ELLA

After

Fig. 4c



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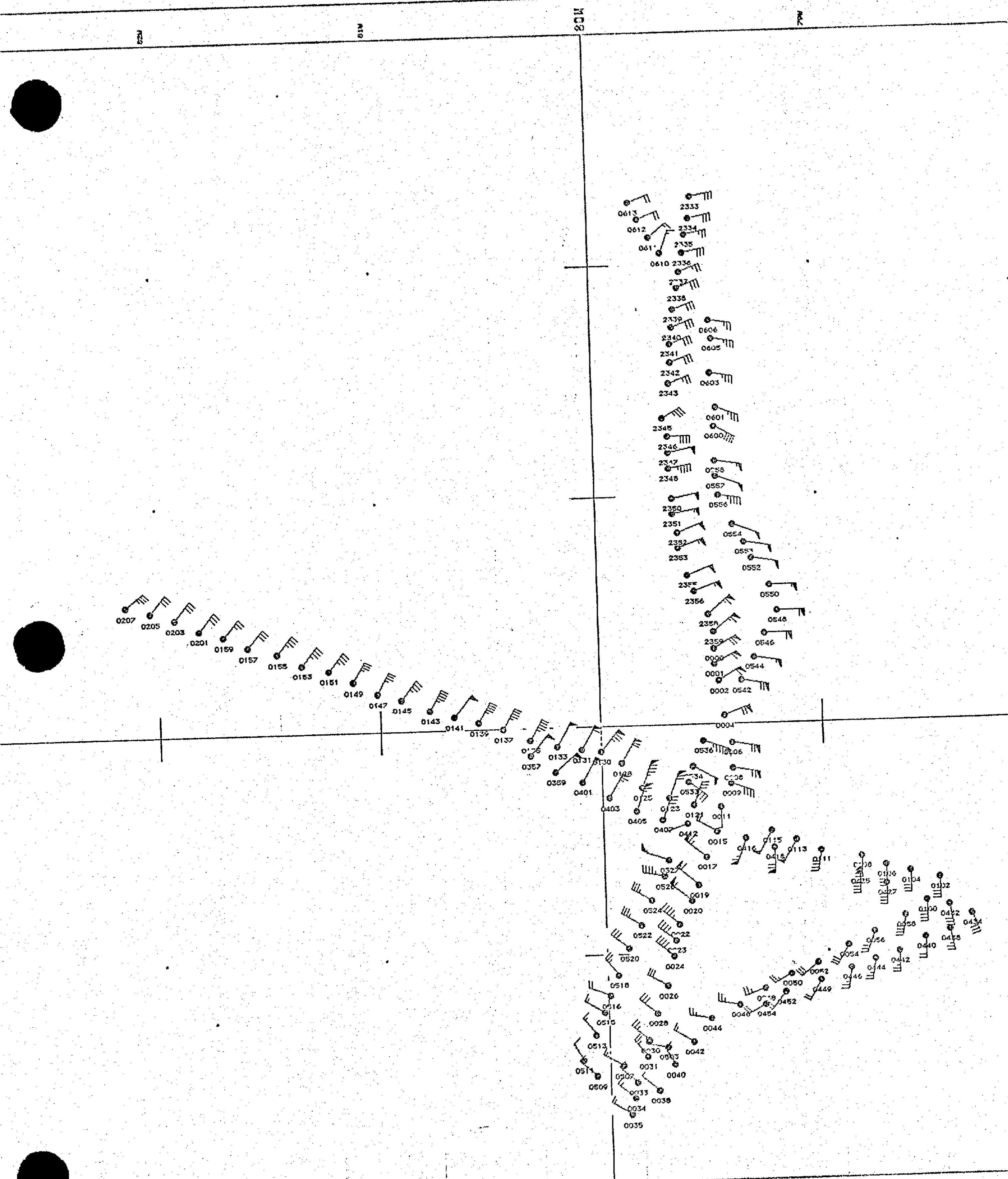
MFM/ASDL DATA PLOT TEST LIVEZEY BIN 02 PLEASE
GRETA

Before

Fig. 4d



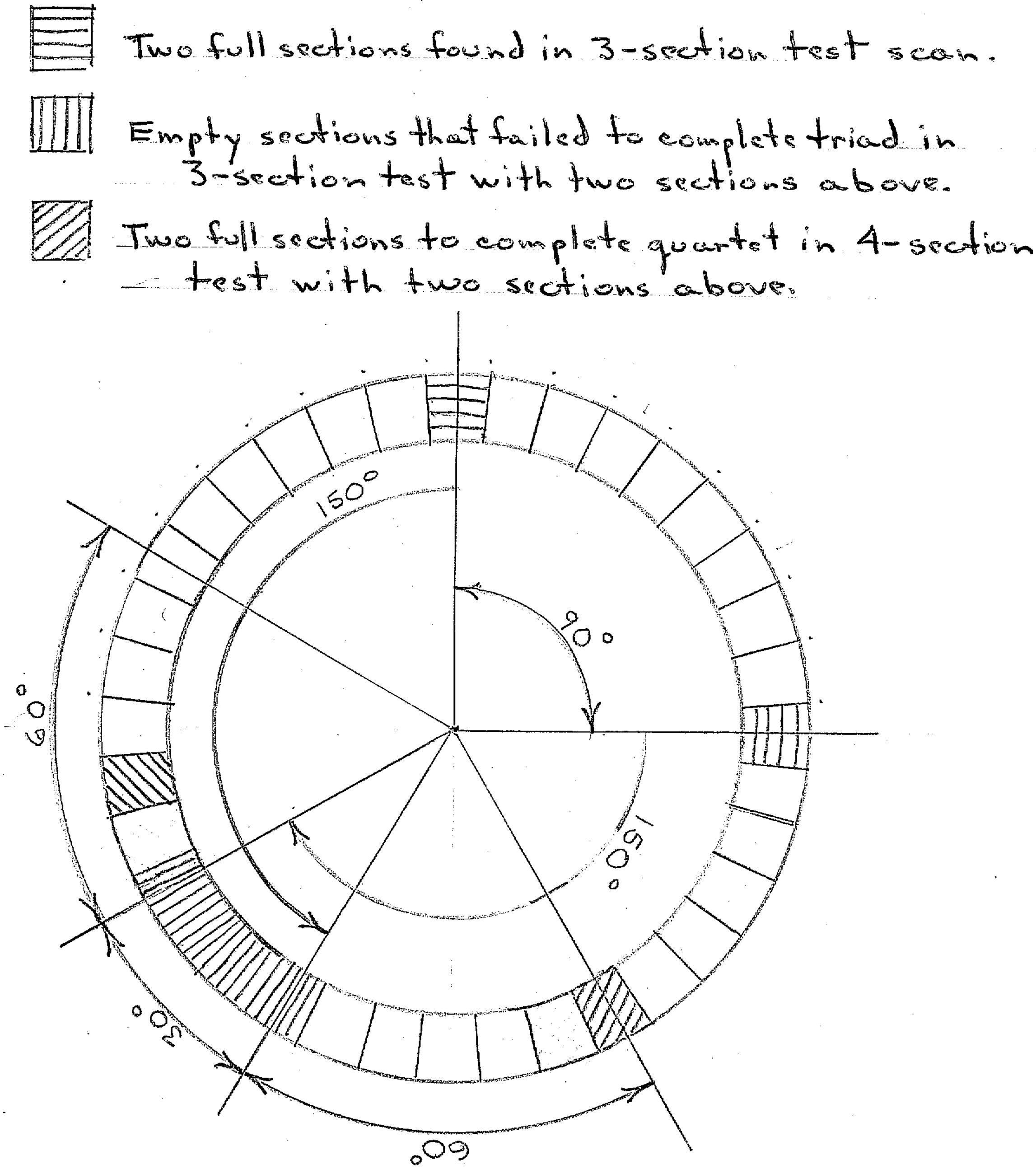
After

ETEOROLOGICAL CENTER

9 17 78

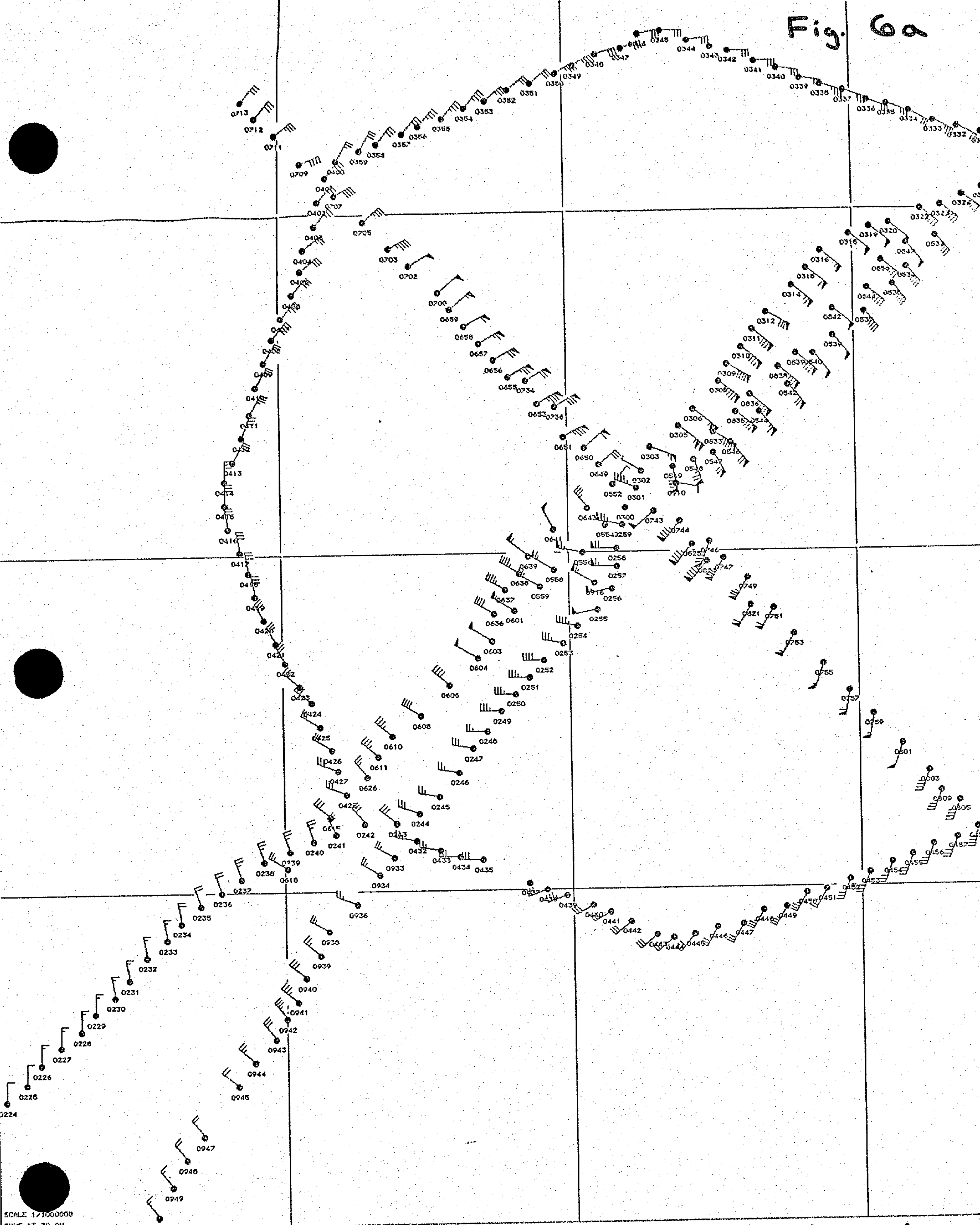
MFM/ASDL DATA PLOT TEST LIVEZEY BIN D2 PLEASE
GRETA

Figure 5



Example of successful 4-section test after unsuccessful 3-section test.

Fig. 6a

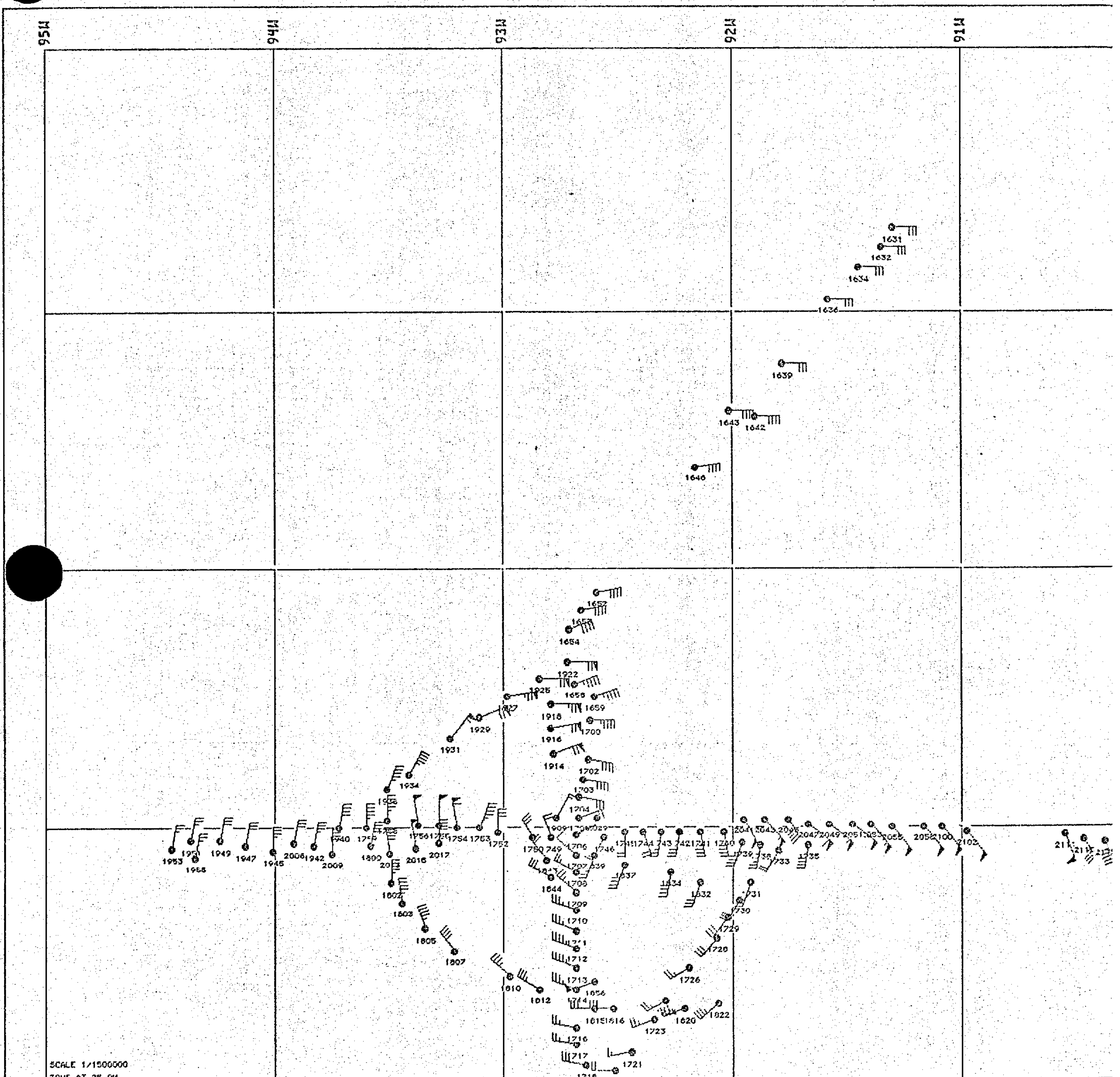


SCALE 1/1000000
TRUE AT 30.0N
NATIONAL METEOROLOGICAL CENTER
ASDL 9 2 78

NFM/ASDL DATA PLOT TEST LIVEZEY BIN 02 PLEASE
NOAA2/NOAA3 ELLA

After recoordinization

Fig. 6b

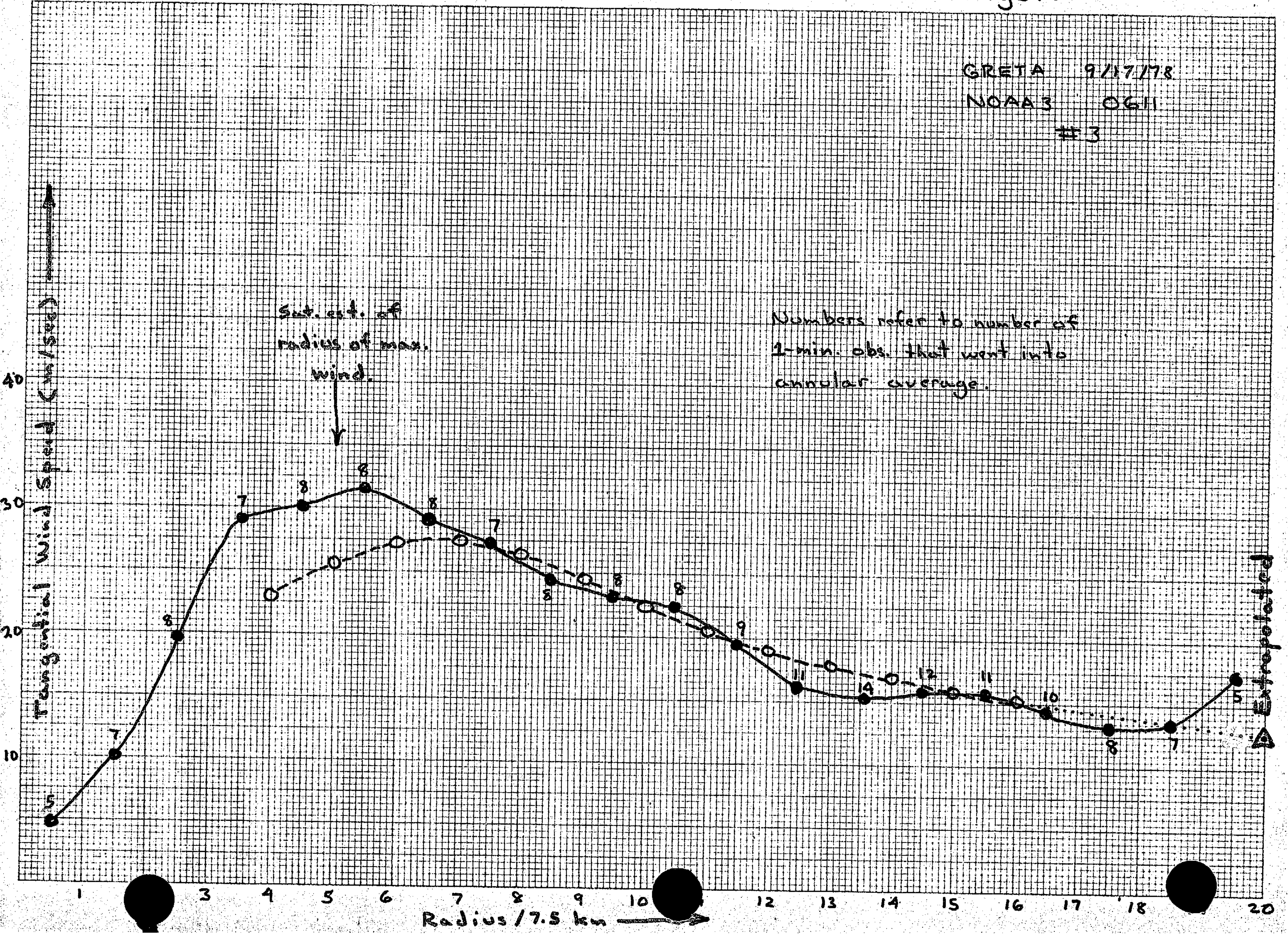


ASDL 9 1 77

MFM/ASDL DATA PLOT TEST LIVEZEY BIN 02 PLEASE
HURRICANE ANITA

After

Figure 7


GRETA 9/17/78
NOAA3 0611
#3
Numbers refer to number of 1-min. obs. that went into annular average.
Sat. est. of radius of max. wind.
Tangential Wind Speed (m/sec)
Radius/7.5 km
Extrapolated
10
20
30
40
1 3 4 5 6 7 8 9 10 12 13 14 15 16 17 18 20