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16. ABSTRACT

The objectives of this study were to develop a predictive algorithm for freeway congestion and to investigate and evaluate the current TSMC definition of freeeway congestion or "bottleneck" conditions. Data were collected along a section of the I-5 mainline northbound beginning at Downtown Station 108 and ending at Montlake Terrace Station 193 using two approaches: (1) time series modeling, and (2) pattern recognition. A pattern recognition approach was used to identify the best criteria for "bottleneck" definition and also to identify the best criteria for prediciting "bottleneck" conditions. The time period for collection was 2:30 to 6:30 p.m. with a data time interval of 20 seconds.

The study concludes that: (1) The current definition of "bottleneck" conditions misses true forced-flow conditions approximately half of the time. A new definition is proposed. (2) A simple method for predicting congestion that can be easily incorporated into the TSMC computer system is proposed. (3) An alternative method of selecting the appropriate metering rate is proposed and further investigation of this criterion is suggested. (4) An improved method of identifying "chattering" errors in loop detectors was discovered as a by-product of the current study. It is recommended that the new criterion be incorporated in the TSMC error analysis routine.

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Final Research Report

Research Project T9233, Task 17
Freeway Congestion Prediction

FREEWAY CONGESTION PREDICTION

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FREEWAY CONGESTION PREDICTION

Introduction. This summary describes the key findings of a WSDOT/TransNow project that is documented more fully in the research report titled, "Freeway Congestion Prediction." The objectives of the study were to develop a predictive algorithm for freeway congestion and to investigate and evaluate the current TSMC definition of freeway congestion or "bottleneck" conditions.

Research Approach. The section of I-5 mainline northbound beginning at Downtown Station 108 and ending at Mountlake Terrace Station 193 was chosen for the study section. Several days' worth of data were collected for this study section. The time period for each day's collection was 2:30 to 6:30 p.m. and the data time interval was 20 seconds. Two types of approaches were investigated: (1) time series modeling, and (2) pattern recognition. A pattern recognition approach was used to identify the best criteria for "bottleneck" definition and also to identify the best criteria for predicting "bottleneck" conditions.

Conclusions and Recommendations. The following conclusions are based on the analysis: (1) "Bottleneck" Definition. A new definition of "bottleneck" conditions is needed. The current definition misses true forced-flow conditions approximately half of the time. A new definition is proposed. (2) Predicting Future Congestion Formation. A simple method for predicting congestion that can be easily incorporated into the TSMC computer system is proposed. (3) Selecting the Appropriate Metering Rate. An alternative method of selecting the appropriate metering rate is proposed and further investigation of this criterion is suggested. (4) Improved Identification of "Chattering" Errors in Loop Detectors. An improved method of identifying "chattering" errors in loop detectors was discovered as a by-product of the current study. It is recommended that the new criterion be incorporated in the TSMC error analysis routine.

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DISCLAIMER

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EXECUTIVE SUMMARY

This report documents the development of an algorithm for predicting freeway congestion or forced flow conditions. The proposed algorithm is simple and easy to incorporate in the TSMC computer system. The investigation also led to a recommendation to replace the current TSMC definition of congestion with a more reliable indicator. A byproduct of the investigation also established an improved method for flagging "chattering" errors in loop detectors.

The study freeway section was a portion of mainline I-5 northbound starting at the downtown Seattle Station 108 and ending at the Montlake Terrace Station 193. Several days' worth of volume and lane-occupancy data were collected for the afternoon time period from 2:30 p.m. to 6:30 p.m.. Time intervals of 20 seconds were chosen for each data collection period.

Important products in this report include the following:

- A simple, and more reliable criterion for the definition of "bottleneck" or forced flow conditions.
- A simple, and reliable criterion for predicting impending congestion or forced flow conditions.
- A proposed variable for improved selection of the appropriate metering rate. (Further analysis of the use of this variable for determining metering rates is recommended for future studies.)

- An improved method of flagging "chattering" loop detector errors (i.e., errors caused by overcounting of vehicles).

All of the criteria proposed in the report are simple and easy to incorporate in the current TSMC computer system. We also propose that further investigation of these criteria be performed with a current follow-up study using neural networks to further identify patterns and rules for ramp metering strategies.

INTRODUCTION

In 1981 the Washington State Department of Transportation (WSDOT) implemented an on-ramp freeway metering system in an effort to achieve higher levels of operating efficiency for the freeway network of the Seattle Metropolitan region. This metering system uses a combination of historical data and real-time data to determine metering rates for on-ramps. Although this ramp metering system has significantly improved the efficiency of the Seattle freeway network, it needs additional improvement. A major drawback of the existing ramp metering system is that it lacks the ability to anticipate future traffic flow conditions, and thus respond and potentially mitigate those conditions before they occur. The current system can only respond to "bottleneck" or forced flow conditions after they occur.

Existing Condition

The WSDOT's Traffic Systems Management Center (TSMC) currently uses two algorithms to regulate on-ramp metering rates: local metering and bottleneck metering (Jacobson et al (4)). The two algorithms use traffic volume and lane occupancy measurements obtained from inductance loop detectors (ILDs) embedded in the pavement. Figure 1 shows the current procedure.

For each station, processing first begins with the local metering algorithm, and then proceeds to the bottleneck algorithm if two traffic flow conditions are met. For the local metering component, the field 170 controller determines the lane occupancy value at each station and then, based on this occupancy value, selects the corresponding predetermined

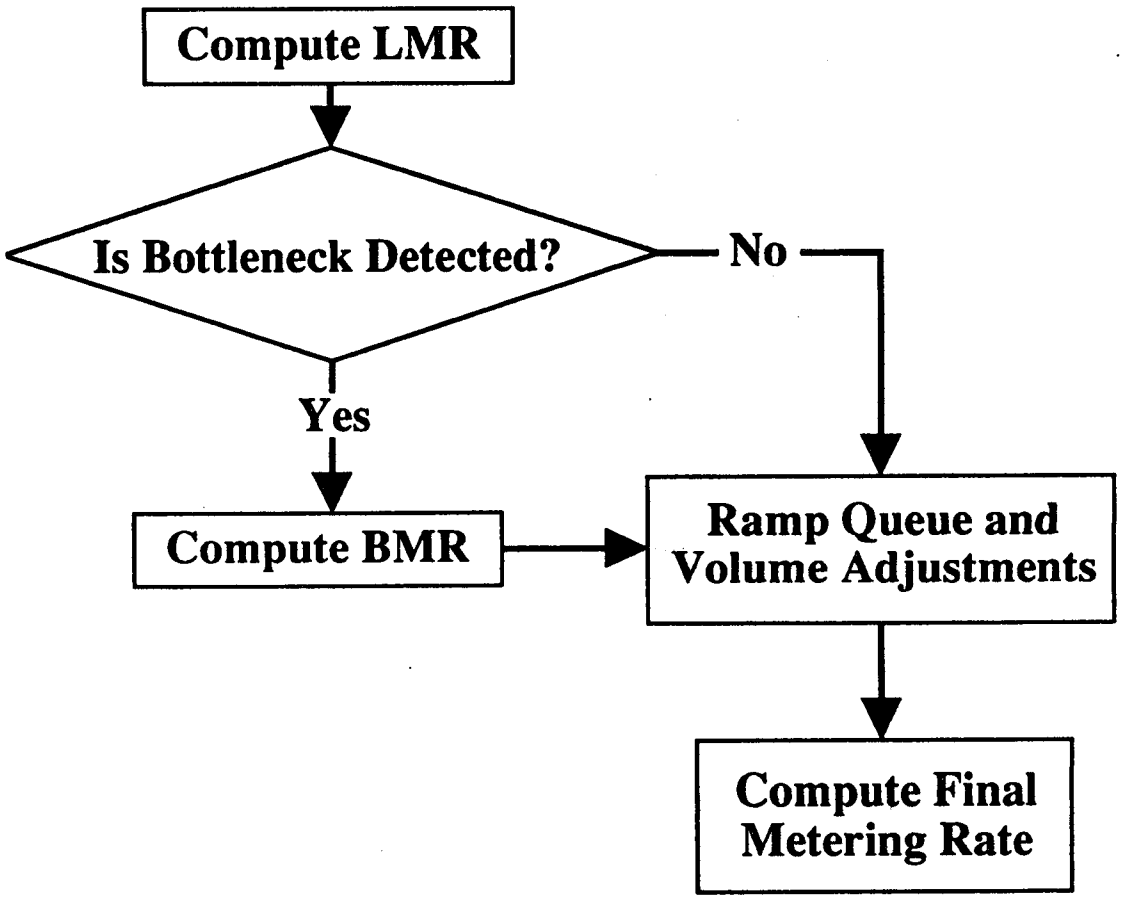


Figure 1. Ramp Metering Control Routine Sequential Logic

local metering rate (LMR) for that ramp. (I.e., the local metering rate is determined by interpolating between several occupancy thresholds and their corresponding rates.)

The algorithm then proceeds to the bottleneck condition-checking component. The computer determines the lane occupancy value of each station and compares that value to the predetermined threshold value of 18. If the lane occupancy value exceeds this threshold value, the computer then calculates the storage rate (SR) for the freeway section immediately upstream of the station in question. A freeway section is defined by two adjacent loop detector stations on the freeway (Figure 2 shows an example freeway section layout). The storage rate is calculated by determining the number of vehicles entering the freeway section at the upstream station (mainline and on-ramps) and subtracting the number of vehicles leaving the freeway section at the downstream section (mainline and off-ramps). If this calculated storage rate is positive, meaning more cars entered the freeway section during the previous time interval than exited it (i.e., vehicles are being stored in the section), then both traffic flow conditions for a "bottleneck" have been met and processing shifts to the bottleneck metering component which determines the bottleneck metering rate (BMR). (If both "bottleneck" conditions are <u>not</u> met, the pre-determined local metering rate is used to regulate on-ramp flows.)

The bottleneck algorithm uses the freeway section's storage rate value to determine metering rates for the upstream ramps. Essentially, this value is the necessary volume reduction for zero storage in the freeway section. Therefore, the upstream on-ramps that are considered to have an influence on this particular freeway section will have their

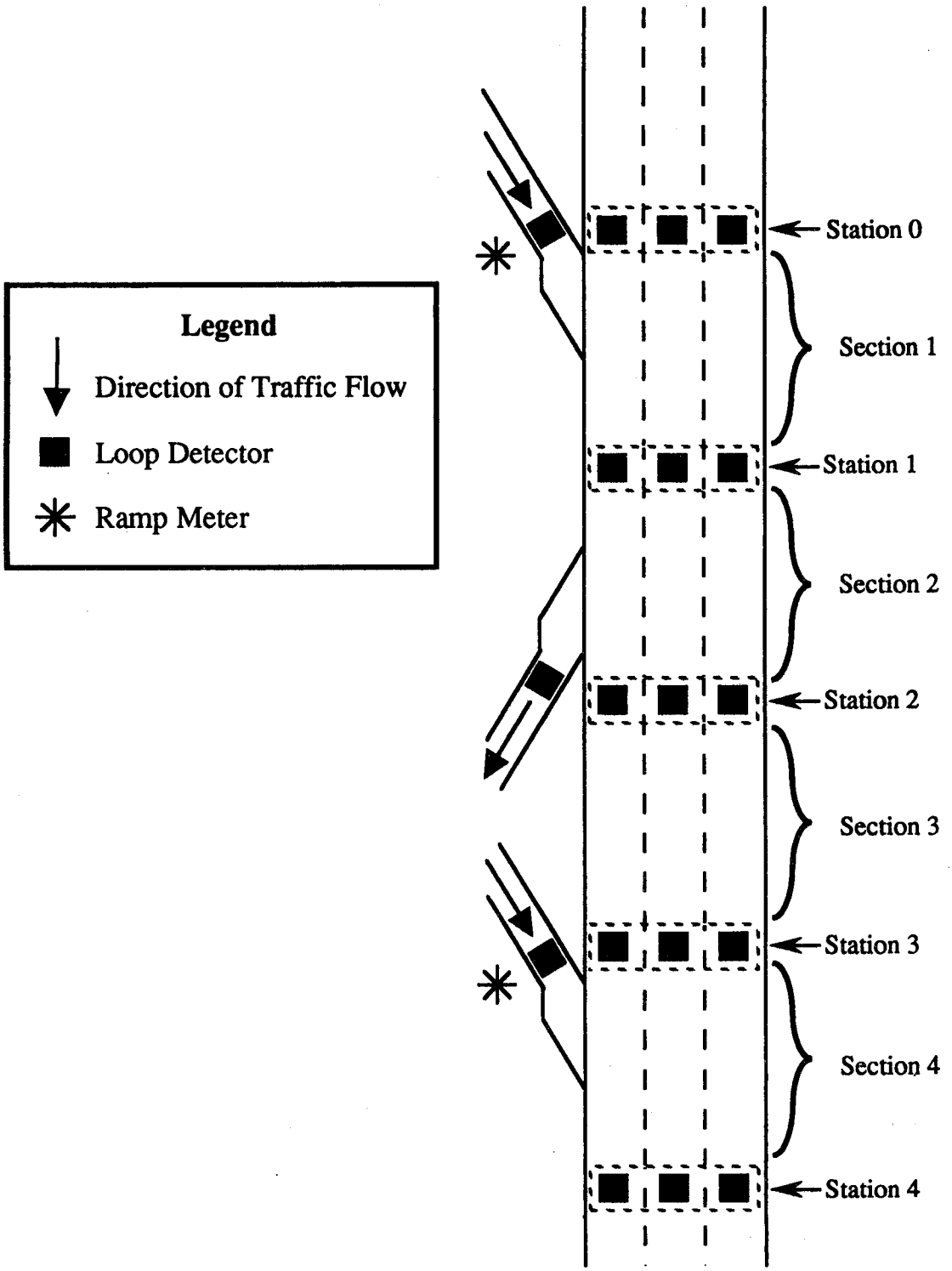


Figure 2. Example Freeway Sections for WSDOT Ramp Metering Algorithms

metering rates reduced by a percentage of the storage rate value proportional to their impact upon the traffic volume in this freeway section. Thus, the total reduction in cars metered onto the freeway is equal to the positive storage rate calculated previously (The metering rate after bottleneck adjustment is subject to further adjustment due to ramp queue length and the min/max rates.).

Desired Condition

While the existing ramp metering control strategy is somewhat effective in reducing total travel delay, it is not effective in anticipating and preventing "bottleneck" (forced flow) conditions before they occur. The nature of the current metering control strategy is that it reacts to forced flow conditions once they have occurred, rather than anticipating and, possibly, preventing them. The goal of this research is to investigate methods that will result in an algorithm that predicts the likely occurrence of bottleneck conditions in freeway sections before they occur. The anticipated effect of such a predictive algorithm will be to eliminate or reduce the onset of forced flow conditions and create a more stable traffic flow for the network.

The predictive algorithm is expected to eventually be incorporated into the TSMC's current ramp metering system. The predictive algorithm will follow the local metering algorithm until it predicts a "bottleneck"; it will then transfer control directly to the bottleneck metering algorithm (or an improved forced flow metering algorithm). If it does not predict a bottleneck, control will continue with the normal bottleneck test condition

routine. (Note: the test that defines forced flow conditions is also part of this study and may be altered in both the predictive and normal routines.)

REVIEW OF PREVIOUS WORK

The purpose of this section is to introduce the reader to previous work in the area of predicting freeway bottlenecks for improved ramp metering control strategies. While much has been done in the more formal area of predicting traffic volumes, little has been done in the area of predicting traffic congestion. Two of the more thoroughly investigated methods for traffic flow prediction are presented briefly here, followed by a comprehensive introduction to statistical pattern recognition.

Time Series Analysis

Least Squares Approach

This method has been investigated in detail by Nihan and Knutson (9) and Nihan and Zhu (10) at the University of Washington. The general form of these models is that downstream volume can be expressed as a function of the sum of fractions of upstream volumes lagged an appropriate amount.

The main goal with these models is to find the appropriate time lags which will indicate the minimum and maximum travel times from upstream stations, and to find the appropriate coefficients at these lags. Nihan and Zhu used spectral analysis and Fourier's transformation of the covariance to determine the lags and ordinary least squares to obtain the coefficients at these lags. Nihan and Knutson regressed a wide range of time lags to identify appropriate lags and again used least squares to determine the coefficients.

The effectiveness of these models was measured by several statistical measures: mean square error (MSE), mean absolute error (MAE), mean absolute error percent (MAE%), and maximum error percent (Emax%).

Both models showed encouraging results for the prediction of traffic volumes using the least squares technique. The main focus of these studies was to develop a model which would be able to "fill-in" missing inductance loop detector data. Thus, the specific issue of integrating this volume prediction method into a loop metering control routine was not addressed.

Box-Jenkins Method

The Box and Jenkins method (2) for time series forecasting can also be used to model the short-term dynamics of freeway traffic flow variables, as results from Ahmed and Cook (1), and from Kyte, et al. have indicated.

The autocorrelation function (the correlation of a variable with its own past) and the cross-correlation functions (the correlation of a variable with another variable's present and past) are then inspected to obtain candidate models. These models all express some variable's current value as a linear combination of its own and other variables' past values. After a comparison of the estimated linear weights of the candidate models, the best model is chosen as the forecaster.

Davis, et al. (3) fit univariate and transfer function models to 1-minute time series data of storage rate and average lane occupancy values using standard Box-Jenkins methods.

These fitted models were then used to forecast 1-minute ahead occupancies and storage rates for the freeway section in question.

Their research showed that forecasted storage rate values tended to hover around the mean value for the time series and ignore extreme values. Their research also showed that forecasted occupancy values tracked the true values, but one minute too late. These results were discouraging because the time series methods tend to forecast average rather than extreme values. However, the extreme values, which characterize the transition from free-flow to forced-flow conditions, are the ones we are trying to forecast.

General Assessment

Although time series analysis proved useful in predicting traffic volume trends, it was best used for filling in missing data and other uses where the average trend is the variable of interest. However, it was determined that this technique was much less useful for predicting minute-by-minute or even smaller time fluctuations in traffic volumes. Since such fluctuations are important to the prediction of impending forced-flow conditions, the rather limited number of studies that applied pattern recognition to this problem were also reviewed and considered for use as part of the current study. These are discussed next.

Statistical Pattern Recognition

Statistical pattern recognition techniques use the principle of data categorization. Existing data are classified into different categories, and then future data are evaluated by identifying their statistical resemblance to a particular category. The research project

described in this report was originally based upon this method and began as an extension of preliminary work done by Davis, et al. (3)

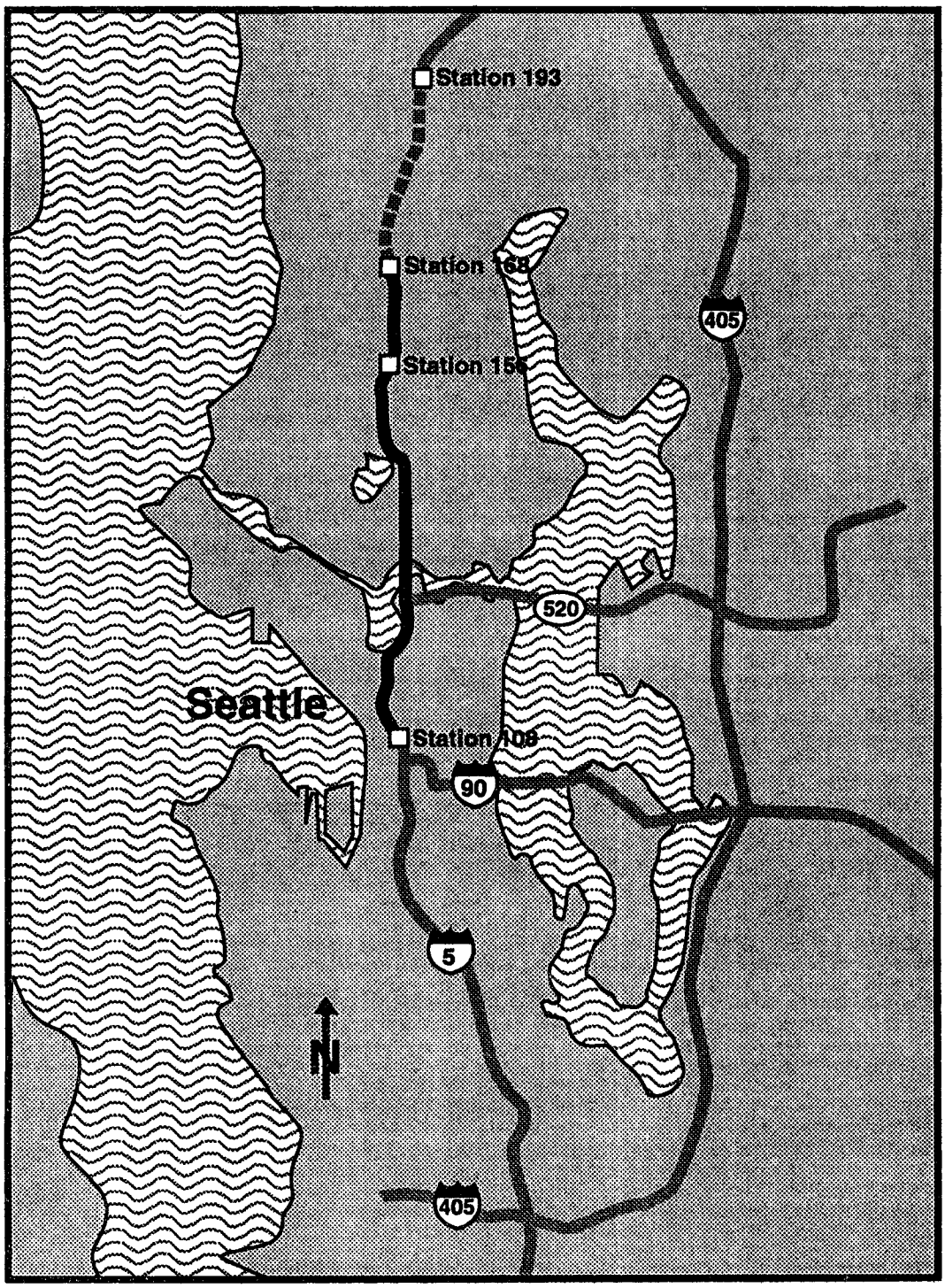
For the purpose of predicting bottlenecks, freeway data were classified into two categories: "bottleneck" intervals and "non-bottleneck" intervals. The Davis, et al. research used the WSDOT definition of a "bottleneck," a freeway section with a positive storage rate and a lane occupancy of greater than 18 percent. Their data sets consisted of volume and lane occupancy measurements collected over two hours in the morning peak and were aggregated into 1-minute intervals. Each of the 1-minute observations were then put into either the "bottleneck" or "non-bottleneck" category based on a simple statistical analysis. The object then was to find variables that were good predictors of bottlenecks. Using the boxplot feature of Minitab (11), Davis, et al. evaluated the storage rate and occupancy measurements at time intervals lagged 1, 2, and 3 minutes for each of three adjacent freeway sections to determine which combination of variables had the best ability to discriminate between "bottleneck" and "non-bottleneck" intervals. Using this method, Davis, et al. found for their study area that the storage rate of the adjacent downstream section lagged 2 minutes and the lane occupancy of the section in question lagged 1 minute were the best predictors for "bottlenecks." A follow-up study by Washburn (12) confirmed this result. However, this led to questions about the WSDOT definition of bottleneck conditions. Further research on this test was needed prior to development of a good predictive algorithm.

RESEARCH APPROACH

Data Collection

Figure 3 shows a map of I-5 mainline northbound beginning at the freeway section between Cherry and Madison Streets downtown (Station 108) and ending at the freeway section between 236th Street SW and 220th Street SW in Mountlake Terrace (Station 193). (See Appendix A for a more detailed rendering of this freeway section including all data stations.) For the present study, we were interested in observing the recurrent bottleneck at NE Northgate Way (Station 156) during the peak p.m. period. Our purpose was to identify the beginning of the bottleneck and observe its dynamic impact on upstream traffic. Lane occupancy and volume data were collected for Stations 108 through 168 for several days in November. The time period for each day's collection was 2:30 to 6:30 p.m. and the data time interval was 20 seconds. Time series graphs of the data by station revealed similar patterns for each day. A typical day (Wednesday, November 10, 1993) was selected for further analysis. Appendix B contains time series graphs of the variables considered for this day.

The original data showed a bottleneck forming well downstream of the Northgate section. Therefore, to investigate the potential beginning of this bottleneck, we extended the study section further north to include the entire stretch of Stations 108 through 193. This was the end of the metered system so that data for stations further upstream were not available.



Location of original study section

Additional mileage included in extended study section

Figure 3. Freeway Study Section

The data for this longer section of northbound I-5 were collected from 2:30 p.m. to 6:30 p.m. on December 15, 1993. Again, the data time interval was 20 seconds. Appendix C shows the time series graphs for the variables considered for this study section.

Pattern Recognition Approach

Previous studies used the definition of bottleneck given by the Washington State Department of Transportation (WSDOT). Here a bottleneck was determined to exist if the lane occupancy at a station exceeded 18 and the storage rate for the section of freeway leading into that station was positive. Using this definition, we used simple statistical tools such as box plots to identify the best predictors of impending bottleneck. A problem with this approach was the definition of congestion or bottleneck conditions itself. Since 20-second storage rates (or 1-minute storage rates, for that matter) tend to oscillate dramatically for both congested and uncongested conditions, the state of bottleneck or non-bottleneck as defined by the WSDOT also varied significantly even during congested conditions.

For example, Figure 4 shows the lane occupancy for Station 168 for every 20 seconds from 2:30 p.m. to 6:30 p.m. on November 10, 1993. It is obvious from the data that congested conditions begin at time interval 276 and continue from that point until the end of the data collection period. This congested period is preceded by a short transition period beginning at time interval 257. Before this transition, the flow at Station 168 appears to have been uncongested. The uncongested period covers the time from 2:30

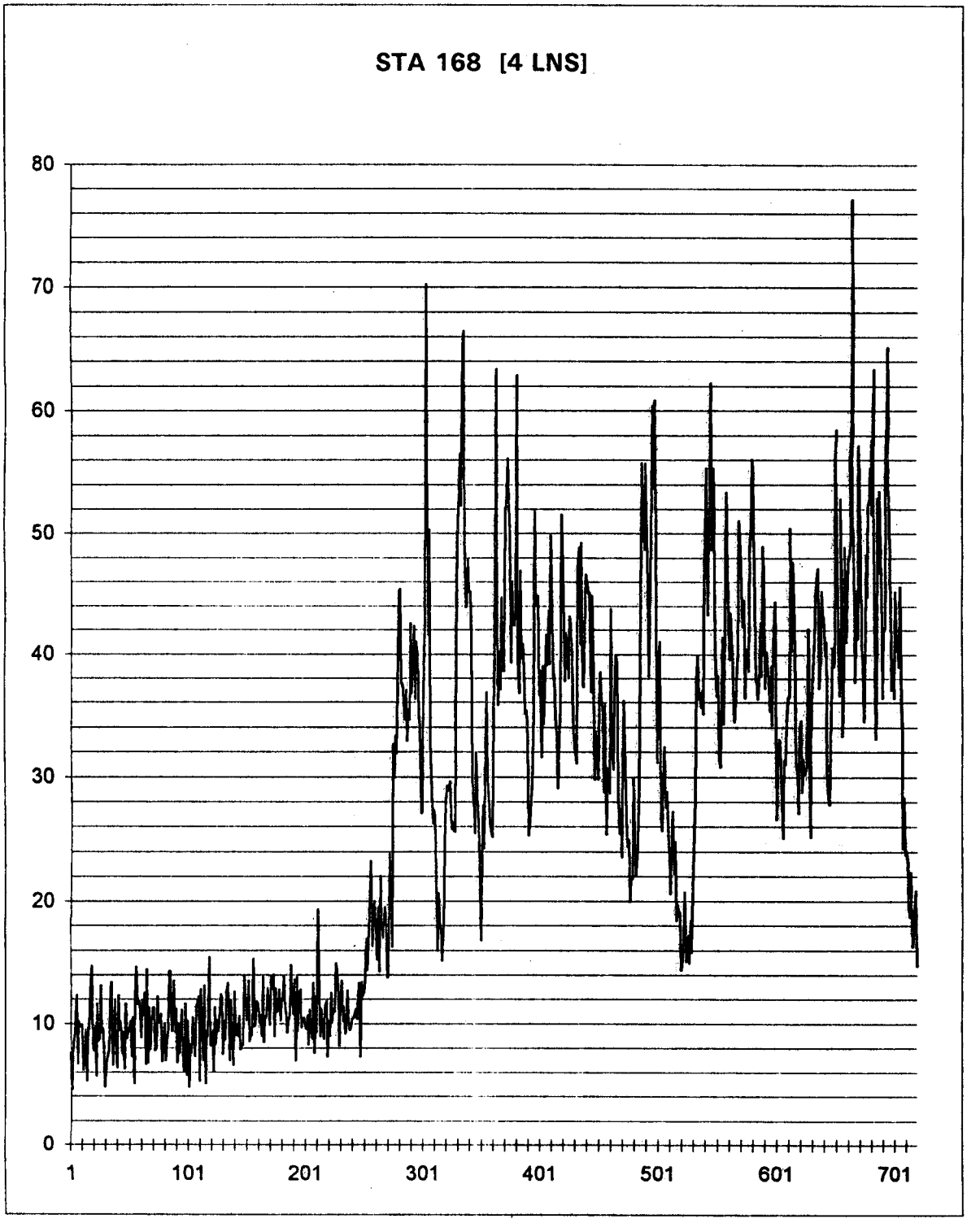


Figure 4. Lane Occupancy vs Time Interval

p.m. (t = 1) to 3:55:40 p.m. (t = 257). The transition period is approximately six minutes. Congested conditions are evident by 4:02 p.m. (t = 276) and continue through the rest of the peak hour. Figure 5 shows the storage rate for this same station and time period. Obviously there are many intervals during the congested period that would, by the WSDOT definition of bottleneck conditions, be observed as non-bottleneck. The same pattern was observed for all stations that made a transition from non-congested to congested conditions (See Appendix B, pp. B1-B4 and Appendix C, pp. C1-C6.). It was therefore determined that a more suitable definition for "bottleneck" conditions was needed before further research could continue.

F/O Ratio as a Congestion Indicator

Although lane occupancy is a good indicator of congestion (see Figure 4), the ratio of flow over occupancy (F/O) was considered to be an even more dramatic indicator of the transition from uncongested to congested conditions. Since this ratio varies directly with speed, it is fairly easy to interpret. Consider the theoretical relationship between speed, flow, and density given below.

$$S = F/D \qquad \text{Equation 1}$$

where

S = space mean speed (miles/hour)

F = flow rate (veh/hour)

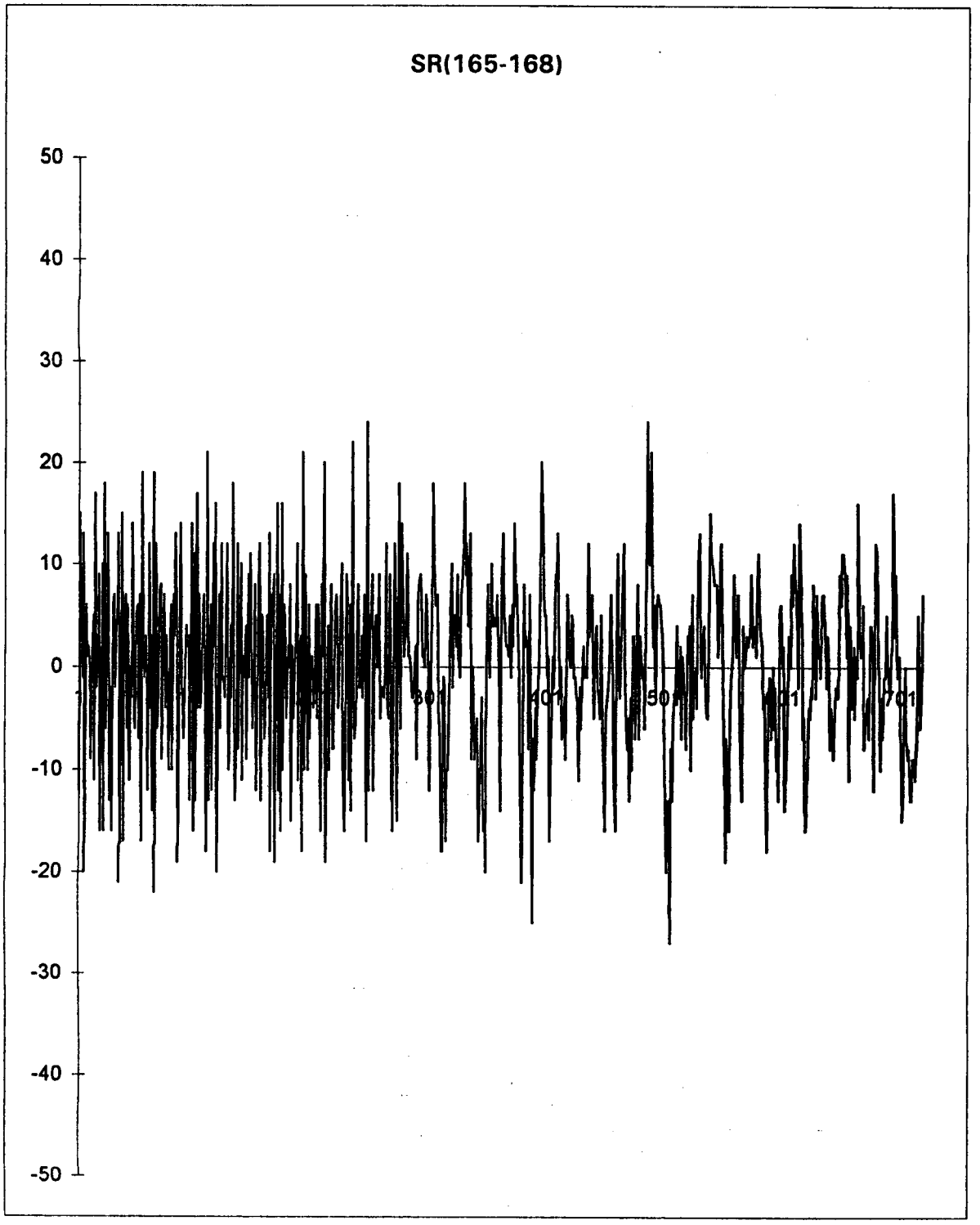


Figure 5. Storage Rate vs Time Interval

D = density (veh/mile)

Density can be expressed as a function of lane occupancy by

$$D = \frac{O}{100}\frac{5280}{Le} = g(O) \qquad \text{Equation 2}$$

where

O = lane occupancy (%)

Le = average effective vehicle length

Thus, for any 20-second time interval,

$$S = (1/g)\,(F/O) \qquad \text{Equation 3}$$

where

g = 52.8/Le

Thus, a higher F/O ratio corresponds to a higher speed and vice versa.

If the average vehicle length of the traffic stream remained constant, g would be constant and F/O would vary linearly with speed. Figure 6 shows the F/O values over time for Station 168 for the November 10, 1993, date. The transition from uncongested to congested conditions is obvious and, once Station 168 experiences congested conditions, it never returns to the higher speed threshold level.

Examples of this dramatic shift in the F/O ratio can be observed for stations all along the freeway study section (See Appendix B pp. B5-B7 and Appendix C pp. C7-C10.). These

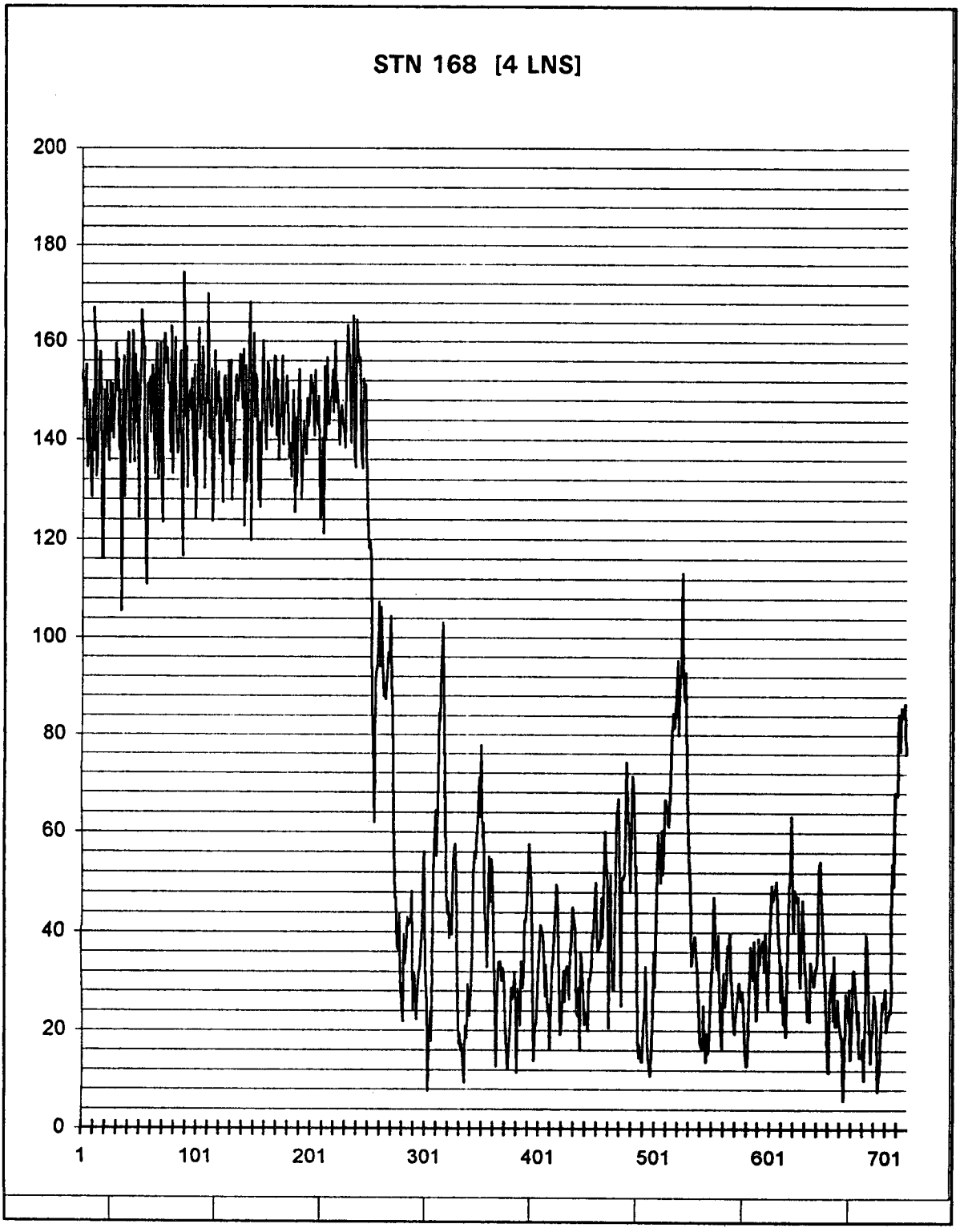


Figure 6. F/O vs Time Interval

observations led the current study to focus on a new approach to congestion prediction which was centered around determining transitional volumes of the F/O ratio that preceded congested conditions. Congested or "bottleneck" conditions were now defined in terms of threshold values of the F/O ratio.

Use of SumSR(t) as a Congestion Indicator

The sum of storage rates for a section of freeway over time is another good indicator of congestion level and is useful to the determination of required ramp metering levels. Since this sum is sensitive to loop detector errors, it also proves to be a useful variable for identifying certain types of "chattering" errors that are not flagged by other criteria. This variable is discussed further in the discussion of research findings.

FINDINGS/DISCUSSION

This section discusses the results of both time series analysis and pattern recognition approaches. Time series models were fit to volume data for various freeway sections to assess the utility of this approach to congestion prediction. Pattern recognition was applied to the F/O variable for the same purpose. In addition, we analyzed the Sum(SR)t variable for its potential use as a congestion indicator and error predictor.

Time Series Analysis

Referring to Appendices B and C, pages B5-B7 and C7-C10, respectively, one can see that the F/O variable has consistent average values for non-congested flow and for congested flow. This distinction is clear and enables us to easily sort the data into congested and uncongested sets. This, of course, is necessary for the pattern recognition approach, but also is useful in identifying the requisite data sets for fitting time series models for both types of conditions. In the model fitting, volume data at each station were related to lagged volume data of the upstream station and the upstream on- and off-ramps for that freeway section. Since a significant change in speed (i.e., a change from uncongested to congested flow) should result in the significance of different lags for the explanatory volume data, two models were fit for each station (one time series model for uncongested flow and one time series model for congested flow).

Figure 7 shows the results for a typical station for the pre-congestion model. Data for time intervals 1 through 200 were used to fit the pre-congestion model, which is shown below:

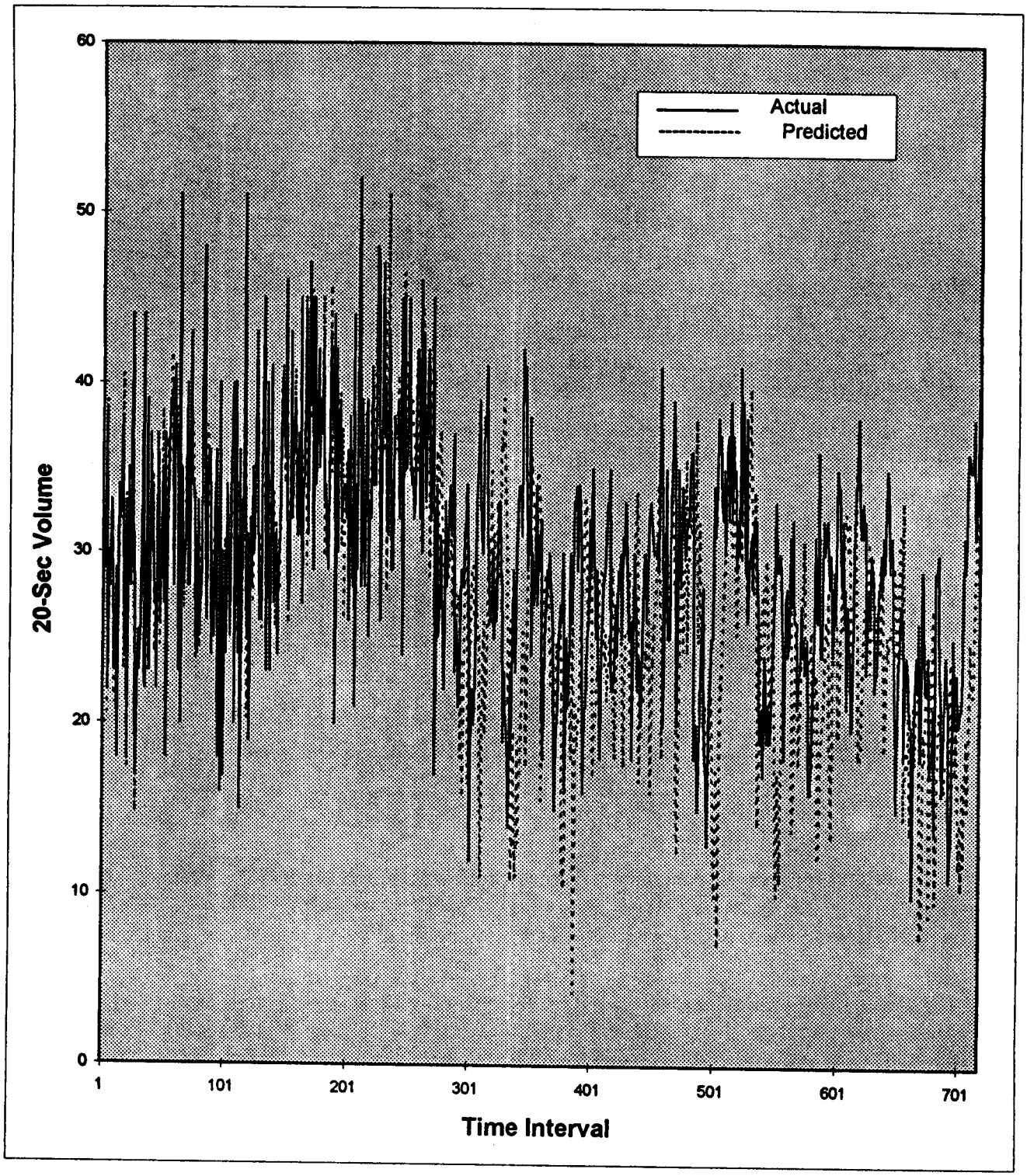


Figure 7. Volume Predictions, Pre-Congestion Model

$$V_{168}(t) = -3.18 + .933\ V_{165}(t-1) + .136\ V_{165}(t-2) - .449\ V_{165x}(t-1) - .231\ V_{165x}(t-2)$$

Equation 4

where

V_{168} = volume at station 168

V_{165} = volume at station 165

V_{165x} = volume at exit ramp 165.

The coefficients were all significant (see Table 1 below). The regression equation had an R^2 of 75%.

Table 1. Pre-Congestion Model Fit

Variable	t-statistic	Significance
constant	-1.74	p = .083
V_{165} (t-1)	23.71	p = .000
V_{165} (t-2)	3.53	p = .001
V_{165x} (t-1)	-5.68	p = .000
V_{165x} (t-2)	-2.91	p = .004

The resulting model was then used to forecast intervals 200 through 720. (Note that this included the transition period where traffic was changing from uncongested to congested.)

The during-congestion time series model for Station 168 was fit using data from time intervals 276 through 475 and was intended to be used to forecast subsequent time intervals 476 through 720. However, this model, fit for the congested data, had a poor R^2 of 10% with the constant providing the major influence. The signs of the coefficients of the other significant variables were also not intuitively correct.

Figure 7 indicates a fairly good tracking of the mean volume for both uncongested and congested data. However, when one looks at the interval-by-interval forecasts, one notes that individual time-interval forecasts are subject to large errors. The average trend, however, is accurately forecast even when it changes from high to low volumes.

Thus, although time series forecasting may not be as useful for predicting upcoming congestion on a minute-by-minute (or, in this case, 20-second by 20-second) basis, it appears to be quite accurate for filling in missing data and for flagging bad volume data.

The models developed for other stations along the route showed similar results.

Pattern Recognition Using F/O as the Congestion Indicator

Figure 6 (previous section) illustrates the dramatic change in the F/O variable that occurs when traffic flow changes from relatively free-flow to forced-flow conditions. Note that, in the case of the bottleneck conditions that formed at Station 168 (and upstream stations subsequently affected by the bottleneck at this station), once the value of F/O dropped below a certain threshold, it remained at the lower value corresponding to forced-flow conditions for the rest of the period. Using simple box plot statistics for all of the affected stations it was determined that the criterion of a value of F/O of 90 or below for two consecutive 20-second intervals was a very accurate indicator of impending forced-flow conditions at the station being observed. By the same token, a value for F/O of 75 or less corresponded to existing forced-flow conditions. Figure 8 shows the F/O values vs. time interval for stations 163, 165, and 168. If we assume that congested or forced flow conditions exist at each station after the first major transition to congested flow (e.g., after

t = 276, 302, and 317 for stations 168, 165, and 163, respectively), then Table 2 below gives the percentage of false positives (FP's) and the percentage of false negatives (FN's) for the TSMC "bottleneck" definition and for the proposed Nihan "bottleneck" definition and predictor. The "bottleneck" prediction for each station was assumed to be a 2-minute-ahead prediction, which was a conservative assumption for the stations in question.

Table 2. Error Results

	TSMC "Bottleneck" Definition	Nihan "Bottleneck" Definition	Nihan "Bottleneck" Predictor
STN 168	0.7% FP 52.5% FN	0.4% FP 6.5% FN	1.1% FP 0.7% FN
STN 165	1.3% FP 55.7% FN	0.3% FP 32.8%FN	0.3% FP 9.3% FN
STN 163	1.9% FP 45.4% FN	0.3% FP 35.0% FN	0.9% FP 9.7% FN

For station 168, where the congested flow condition is most obvious throughout the period, the TSMC "bottleneck" definition misses the forced flow condition over half the time (false negatives), while the proposed Nihan definition misses only 6.5% of the time. The proposed Nihan predictor misses less than 1 percent of the time. All approaches do well on false positives, i.e., they do not often predict a forced-flow condition when it does not exist. For stations 165 and 163, the forced-flow conditions do not appear to be completely stable throughout the period assumed as congested. Consequently, some of the false negatives may correspond to short periods of relatively improved flow. Nevertheless, the traffic during this period is, for the most part, congested. For both of

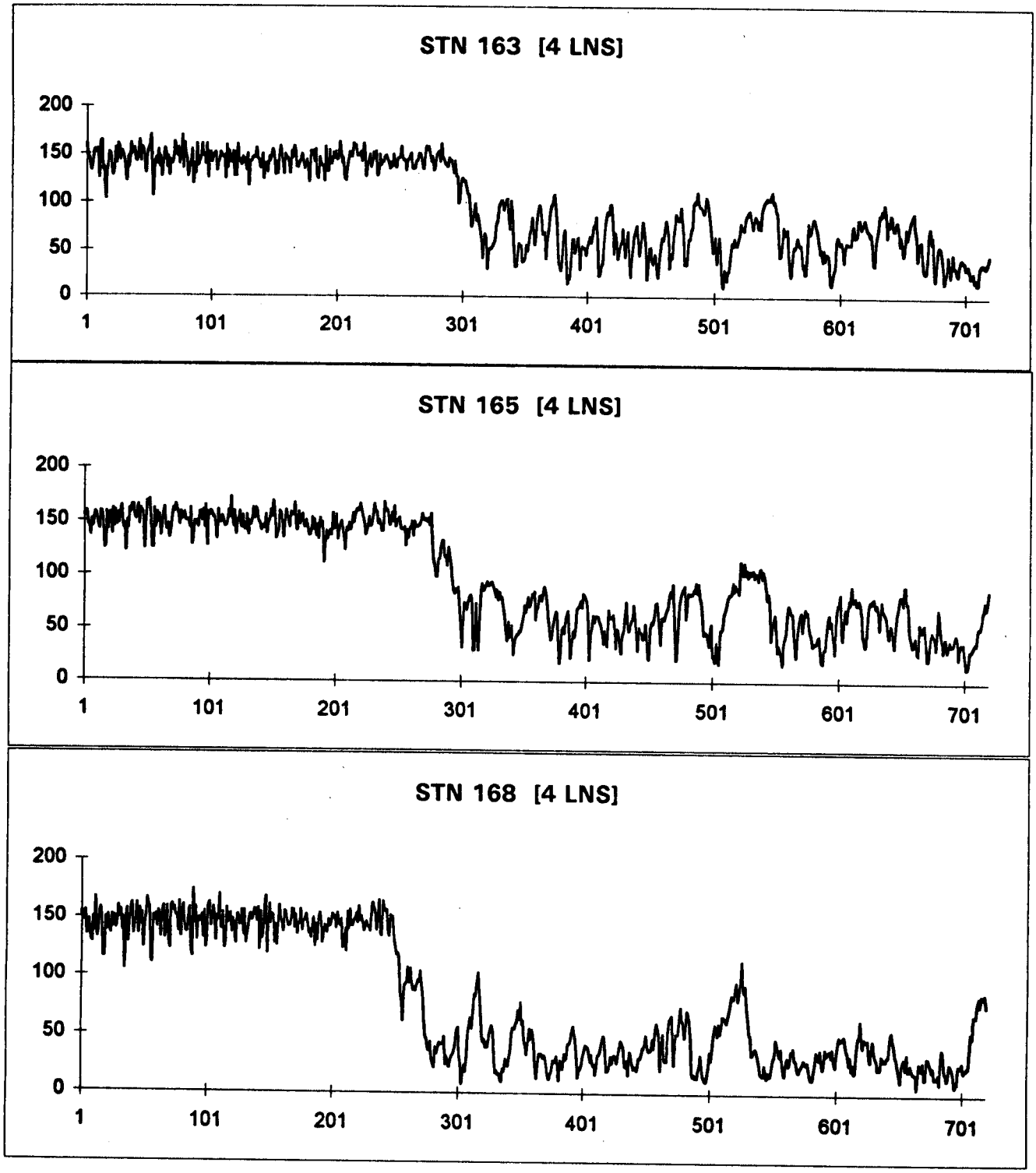


Figure 8. F/O Values for 3 Adjacent Stations

these stations the proposed bottleneck definition gives better results then the current TSMC definition, and the proposed predictor is an improvement over both.

Returning to the proposed "bottleneck" definition, we can add to our predictive approach by observing downstream stations that have already reached the F/O ≤ 75 criterion. When a station first exhibits this condition, there may be several minutes' warning before the "bottleneck" condition travels upstream. This could provide enough warning in some cases to prevent this type of shock wave effect. For example, Figure 9 shows the "bottleneck" progression from Station 168 to upstream Stations. The figure indicates that Station 168 first exhibits this "bottleneck" criterion (i.e., F/O(t)≤75 <u>and</u> F/O(t-1)≤75) at time interval 276 corresponding to 4:02 p.m.. The "bottleneck" conditions do not begin at the Station 165 directly upstream until time interval 302, which is 8⅔ minutes later. "Bottleneck" conditions forming at subsequent upstream stations 163 and 161 occur at intervals t = 317, and t = 351, respectively. Thus the "bottleneck" starting at Station 168 does not travel back to Stations 163 and 161 until 13⅔ and 25 minutes later, respectively. Using the proposed new criterion for "bottleneck" conditions eliminates the problem of oscillation that occurs with the original TSMC definition. As one can note from the figures, once the F/O ratio falls below a certain value it remains at the new threshold until the forced-flow condition changes. Using the new bottleneck criterion, one can quickly identify a station where a bottleneck is forming and make corresponding changes to the upstream metering rate with the goal of reducing or eliminating the shock wave effect.

This type of warning can result in congested flows of shorter duration covering a shorter length of freeway.

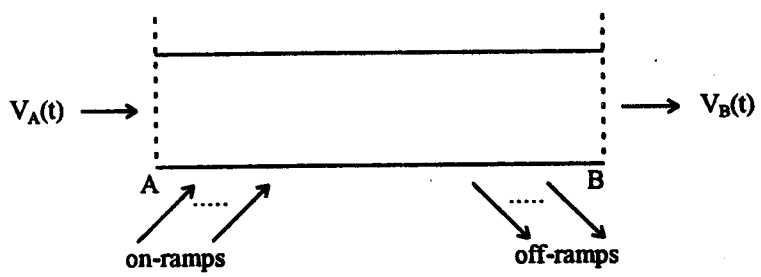
The F/O ratio can also be used to give a good indication of impending congestion <u>before</u> it forms at any station. The criterion of F/O(t)≤90 <u>and</u> F/O(t-1)≤90 is a very accurate indicator that traffic is in the transition period (either from uncongested to congested or vice versa). For example, the transition period for Station 168 is from t = 257 to t = 276 ($6^1/_3$ minutes). The F/O criterion stated above occurs immediately at t=258. This gives a 6-minute warning at Station 168. Similarly for Station 165, the transition period is t = 281 to t = 302. The forming-bottleneck criteria (F/O(t) and F/O(t-1), both ≤ 90) occur at t = 284 for this Station, giving it a 6-minute warning. Ramp metering changes based on this criterion could result in fewer instances of bottleneck conditions. In those cases where the congested conditions could not be completely eliminated, this type of advance warning could help delay and shorten the duration of congested flow.

Using the F/O variable to predict impending congestion, one now needs to decide the best ramp metering strategy for keeping the desired threshold density values from being exceeded. At the current time, the TSMC simply uses the storage rate, SR(t) as the number of extra vehicles to keep from entering the system. While this makes sense intuitively, the SR(t) variable does fluctuate widely from interval to interval and the result is a metering strategy that may oscillate too drastically for the desired impact. If, instead, we look at the running sum of the storage rate over time we get a better feeling for the approach of critical density values and a better sense of a more consistent metering strategy for forced-flow conditions.

A discussion of the possible use of the SumSR(t) variable is presented in the next two sections.

Use of SumSR(t) as a Metering Indicator

Although storage rate for any interval, t, does not appear to provide a very helpful indicator for determining the best level of ramp control (see Figure 4, previous section), the <u>sum</u> of storage rates over time can be very useful as a congestion or density predictor and indicator of the required level of ramp metering. To illustrate this, consider the section of freeway shown below.



This freeway section has a length, ℓ, and an upstream mainline volume during interval, t, of $V_A(t)$, with a corresponding downstream mainline volume during the same interval of $V_B(t)$. Let $V_{on}(t)$ equal total volume entering the freeway section during interval t via the on-ramps, and let $V_{off}(t)$ equal total volume exiting the freeway section during interval t via the off-ramps. We can define the storage rate at the end of interval t as

$$SR(t) = V_B(t) + V_{off}(t) - V_A(t) - V_{on}(t). \qquad \text{Equation 5}$$

This is the total volume exiting the section during interval t minus the total volume entering the section during interval t. Also assume that we know N(1), the total number

of vehicles in the section at the beginning of interval t = 1. Then $N(1)/\ell$ equals the density, D(1), of the section at the start of interval t = . For subsequent time intervals

$$
\begin{aligned}
N(2) &= N(1) + SR(1) \\
N(3) &= N(2) + SR(2) = N(1) + SR(1) + SR(2) \\
&\vdots \qquad\qquad \vdots \\
N(T) &= N(1) + \sum_{t=2}^{T} SR(t-1)
\end{aligned}
\qquad \text{Equation 6}
$$

Dividing the equation by length, ℓ, we get

$$
D(T) = D(1) + \frac{1}{\ell} \sum_{t=2}^{T} SR(t-1) \qquad \text{Equation 7}
$$

Thus we can express the density at the beginning of interval t = T as a function of the density at the beginning of interval t = 1 and the sum of storage rates from then until the beginning of interval T. If we start the calculation during a time of very low density, the first term may be considered negligible or, at least, easily approximated based on general level of service (LOS), i.e., free flow speed conditions. If we have a good estimate of this initial density, then calculation of the running sum of SR(t) over time gives us a good estimate of density at the beginning of any interval and therefore a good indicator of approaching congestion. Also, since we have a good approximation of expected density for that interval, we have a good indicator as to the level of ramp metering required upstream to reduce the volumes entering the section.

Since storage rate is already calculated in the current TSMC algorithm, and a running sum would be easy to incorporate, this appears to be an additional variable that should be

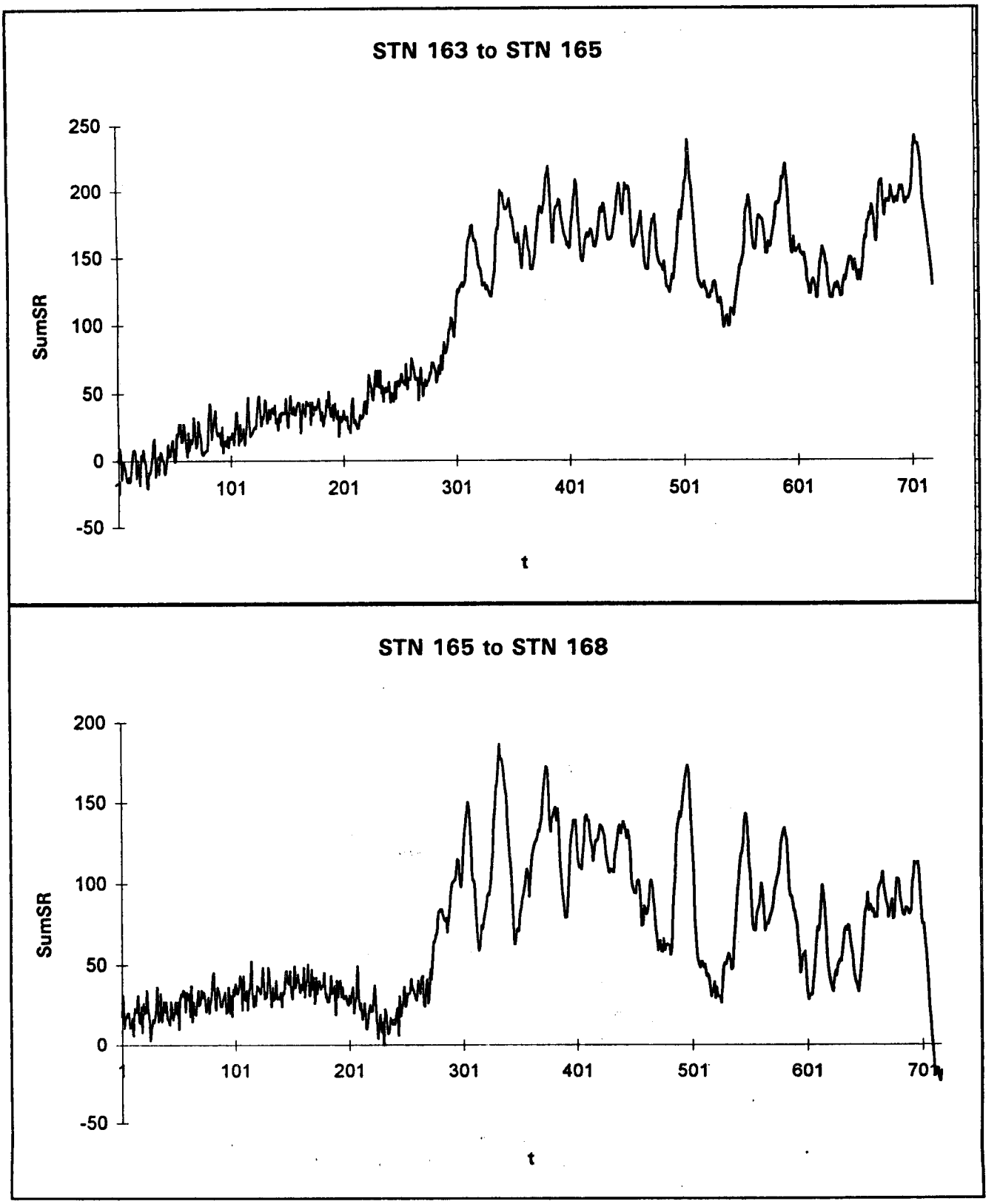


Figure 9. SumSR(t) vs Time Interval for 2 Freeway Sections

considered in future algorithm development. Figure 9 shows how this variable changed for two freeway sections as they went from noncongested to congested conditions. The section of freeway bordered by Stations 163 and 165 is 0.4 miles long. Note that the SumSR(t) variable does not exceed a maximum of 241 vehicles, which, when divided by the section length and number of lanes, equals 150.6 vehicles per lane-mile. Similarly, for the freeway section bordered by Sections 165 and 168, SumSR(t) does not exceed 186 vehicles, which equals a maximum of 116.3 vehicles per lane-mile. If there is no error in the loop detection system, and the data being received are reliable, the SumSR(t) variable should never exceed jam density.

Use of SumSR(t) as a "Chattering" Flag

One serendipitous finding of the current research was the potential use of the SumSR(t) variable for screening "chattering" errors. Such errors occur when a loop detector counts more vehicles than the number actually passing over the detector. The current flag used by the TSMC for catching such errors is to simply flag all 20-second intervals with counts of 17 vehicles or more as instances of chattering.* Of course this represents a per lane volume of over 3,000 vehicles per hour, which is an unrealistically high count. This simple flag does not catch chattering that may occur where realistic volumes are still counted. Thus a loop that is chattering but not giving unrealistically high volume counts will not be flagged under the current setup.

* The 170 ramp meter controllers also flag chattering if a certain number of "hits" (3 or more) occur in 1 second.

As noted in the previous section, the SumSR(t) variable cannot, by definition, exceed a fixed maximum number (i.e., jam density). If, however, one of the loops is creating a consistently positive measurement error, the SumSR(t) variable will either increase or decrease continuously (depending upon the location of the defective loop).

Figure 10 shows the time series of SumSR(t) values for the section of freeway located between Stations 156 and 159. Since the SumSR(t) variable is decreasing continuously, we expect a problem with one of the loops counting volumes entering the section. Similarly, for the section between Stations 161 and 163 the SumSR(t) variable is increasing continuously, so we expect a problem with the exiting station volumes. In fact, there were three flags for chattering for Station 163 based on the current TSMC rule (Vol20 $\geq$ 17). However, when these three intervals were removed, the problem still existed (i.e., SumSR(t) increased continuously). One concludes, therefore, that the chattering problem is more serious than may be indicated by the current screening technique. Since the SumSR(t) variable is very easy to incorporate into the current system, it is suggested that this be used as an additional method of flagging chattering errors.

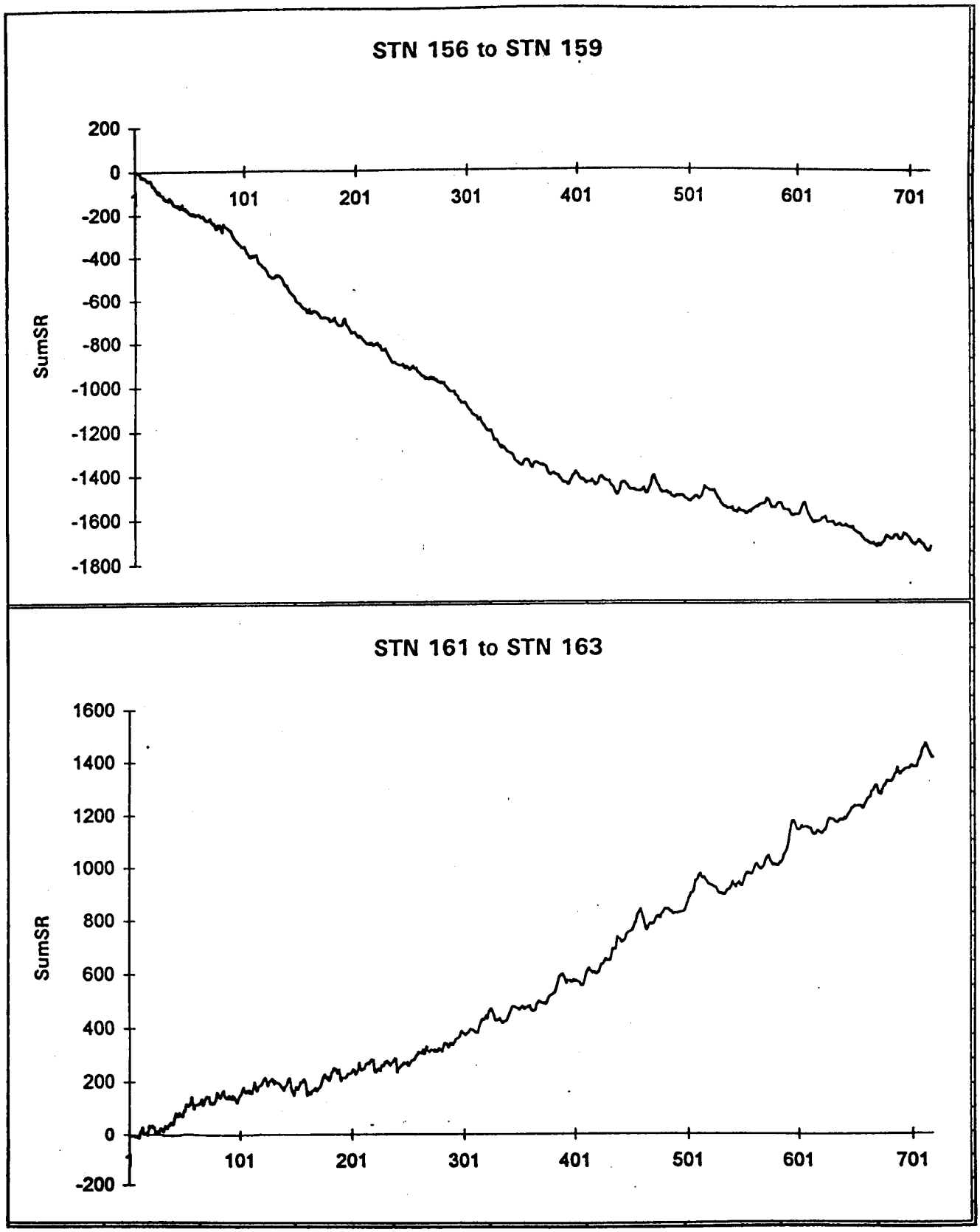


Figure 10. Examples of SumSR(t) as a Chattering Error Flag

CONCLUSIONS AND RECOMMENDATIONS

New Definition for "Bottleneck" or Congestion Needed

The current definition of forced-flow conditions used by the TSMC flags such conditions about half of the time (i.e., produces approximately 50% false negative results). This is apparent in the definition itself since a positive storage rate is one of the criteria for determining "bottleneck" conditions. However, as time series plots of key variables for several stations show, storage rate fluctuates between positive and negative values from interval to interval, regardless of the existence of congested or uncongested conditions. A more reliable, and simpler criterion for identifying current congested conditions allows the use of the flow to occupancy (F/O) ratio, which varies monotonically with speed. The criterion that F/O $\leq$ 75 for the current time interval and the previous time interval appears to be the best choice for the stations analyzed in this study. The calculation can easily be incorporated in the TSMC computer system and should result in fewer false positive <u>and</u> false negative results in assessing current conditions.

Predicting Future Congestion Formation

There is normally a transition period of several minutes when traffic first changes from uncongested to congested conditions at a station. A good indicator of when traffic flow is entering this transition period will provide a few minutes of warning of impending congestion. Even a 2-minute warning is useful (although, for the stations tested, the selected criterion provided an even earlier flag). The criterion selected for identification of the transition period was a value of F/O $\leq$ 90 for the current time interval and the

previous time interval. For the stations studied, this predictor provided a false positive rate of 1% or less and a false negative rate of less than 10%. If no "bottleneck" conditions exist along the study section during a particular time period, this criterion will identify the first station to enter the transition point, and, therefore the point at which a bottleneck may be forming. Advance warning of such a condition may lead to metering that postpones, prevents, or diminishes the impact of the impending congested conditions.

Predicting Shock Waves

Forced flow conditions that form at one station normally travel upstream to create forced flow conditions at upstream stations as well. Identifying a "bottleneck" as soon as it occurs at the first downstream station using the F/O $\leq$ 75 criterion for "bottleneck" definition gives the next closest upstream station several minutes of warning before it also becomes congested. Again, such a warning may lead to metering rates that can alleviate some of the problem before it travels upstream. Since the F/O variable is simple to incorporate in the flagging system, keeping track of this value for stations immediately downstream from the station in question provides another easy check for impending congestion.

Selecting the Appropriate Metering Rate

Currently the metering rate chosen once "bottleneck" conditions have been determined is based on the positive storage rate of vehicles for the section. Although this makes sense intuitively, in practice the storage rate variable oscillates between positive and negative values, and this can result in a metering approach that is also very oscillating and less

effective than other possible approaches. Since the SumSR(t) variable is directly related to density, and since this variable does not fluctuate, it may be a better indicator of the amount of metering required over a section over several minutes' time to maintain the best traffic flow. If we start summing the SR(t) variable during a time of very low density, then we can get a good estimate of initial density, and calculation of the running sum of SR(t) over time gives us a good estimate of density at the beginning of any interval and, therefore, a good indicator of the level of ramp metering required.

Since storage rate is already calculated in the current TSMC algorithm, and a running sum would be easy to incorporate, this appears to be an additional variable that should be considered in future algorithm development.

Use of SumSR(t) as a "Chattering" Flag

If there is no error in the loop detector system, and the data being received are reliable, the SumSR(t) variable should never exceed jam density. However, if there is a consistent positive measurement error at one of the stations bordering the freeway section in question, the SumSR(t) variable will either increase or decrease continuously. This is a very simple and useful flag for identifying "chattering" errors in loop detectors (i.e., when too many vehicles are being counted). It has the advantage of catching not only the obviously large errors, but also identifying chattering at loops where the resulting volume counts may still appear realistic. We recommend that this variable be incorporated in the TSMC error analysis routine.

Future Study Using Neural Networks

Because of some of the problems inherent in trying out the criteria suggested by the current research on-line, the current study recommends further analysis of the F/O and the SumSR variables using neural networks to further identify patterns and rules for ramp metering strategies. A follow-up project using neural networks to carry these investigations further is now in progress.

ACKNOWLEDGEMENTS

A special thanks goes to Scott Washburn for preliminary studies which raised questions about the current TSMC definition of "bottleneck" conditions. Scott's preliminary work with time-series analysis and pattern recognition helped set up the research approach that was finally adopted. Thanks also go to Abel Wong for preparing the graphs contained in Appendix C. The author would also like to recognize the contributions of Les Jacobson, Marty Pietz, Pete Briglia, Mark Morse, Les Rubstello, Dan Dailey, Larry Senn, Cindy Taylor, and Deirdre Meldrum for comments provided during meetings covering the preliminary results of this study.

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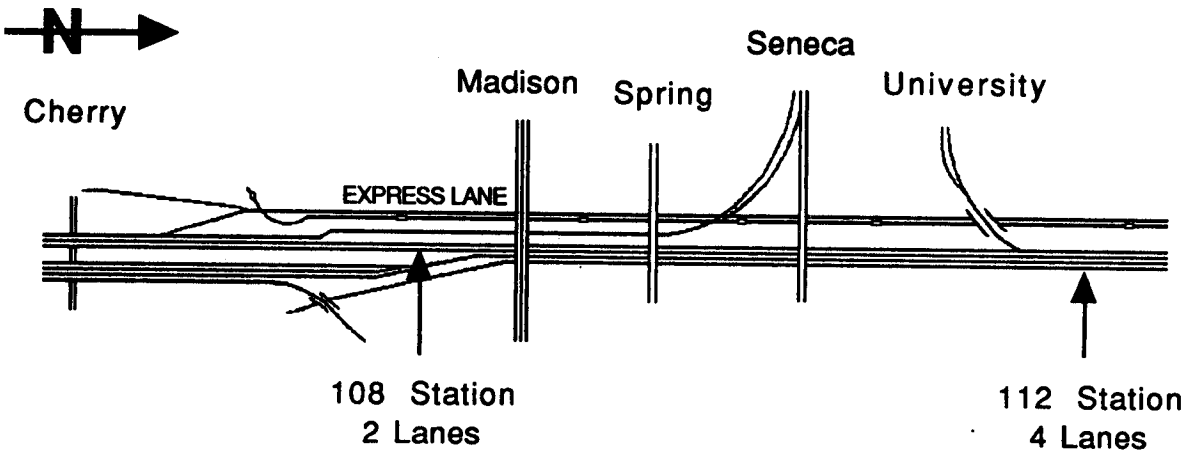
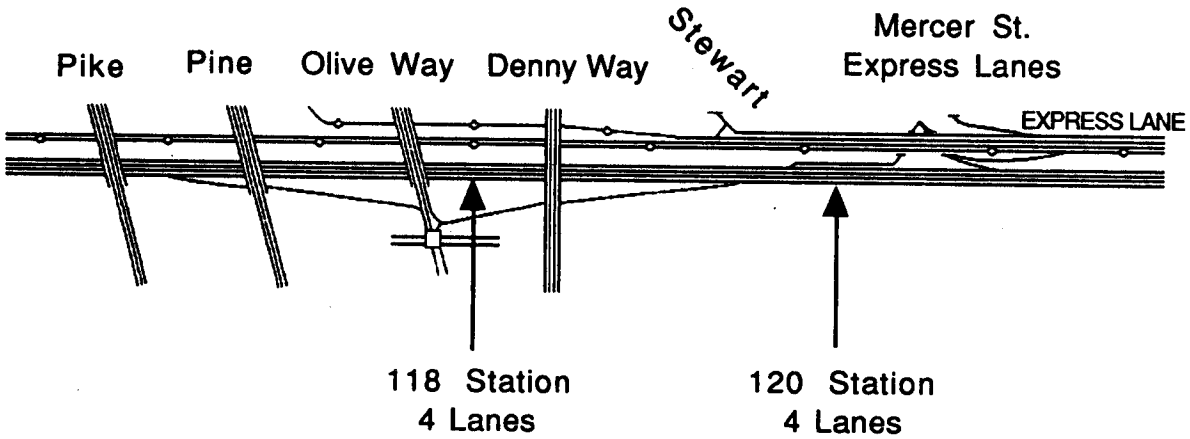
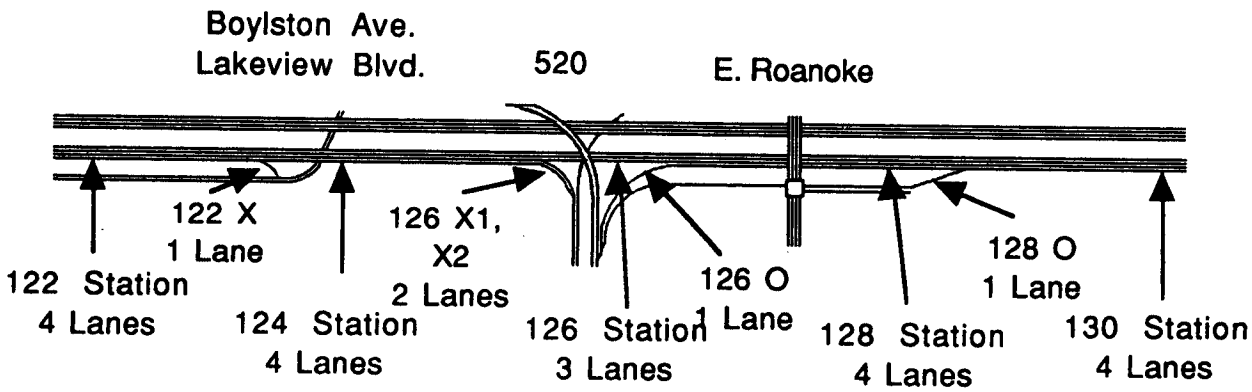
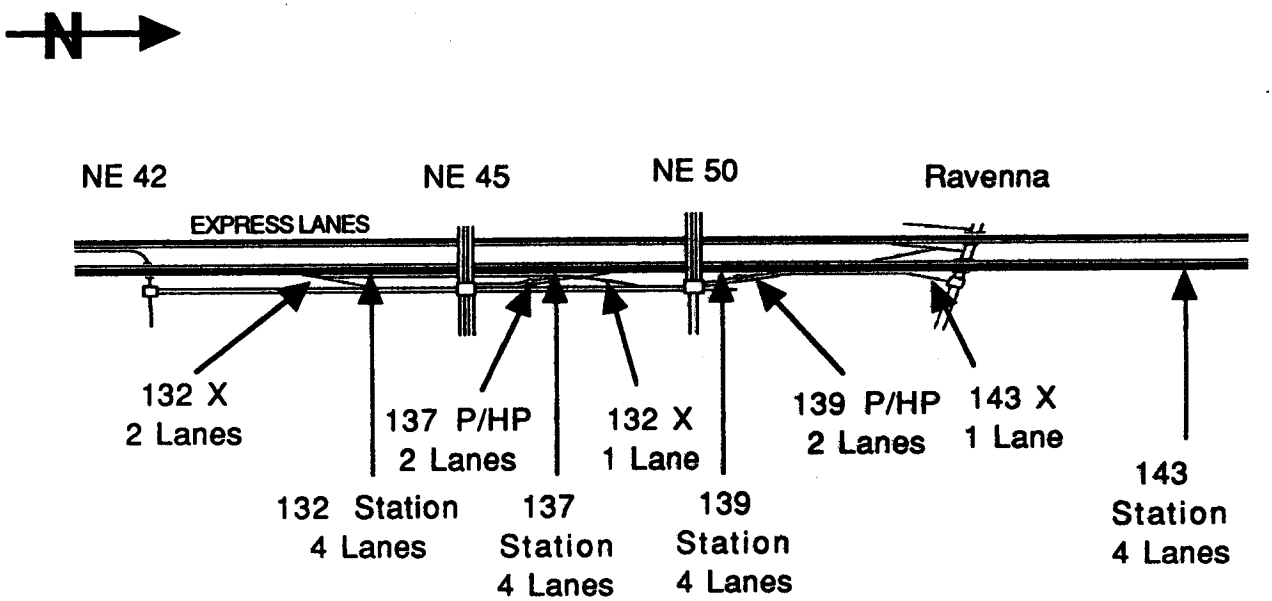
APPENDIX A: DETAILED FREEWAY STUDY SECTION

Freeway Study Section








N
NE 42
NE 45
NE 50
Ravenna
EXPRESS LANES
132 X
2 Lanes
137 P/HP
2 Lanes
132 X
1 Lane
139 P/HP
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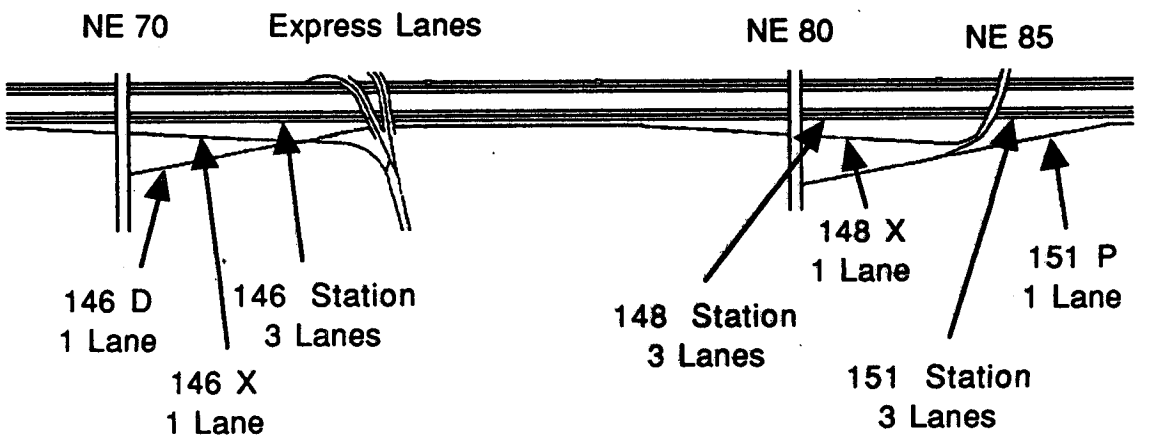
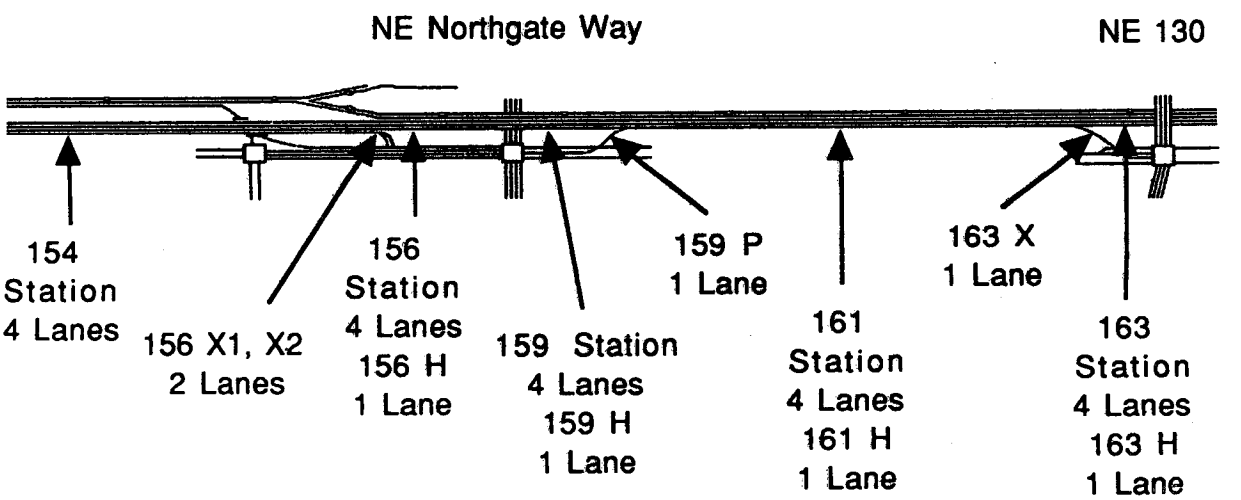
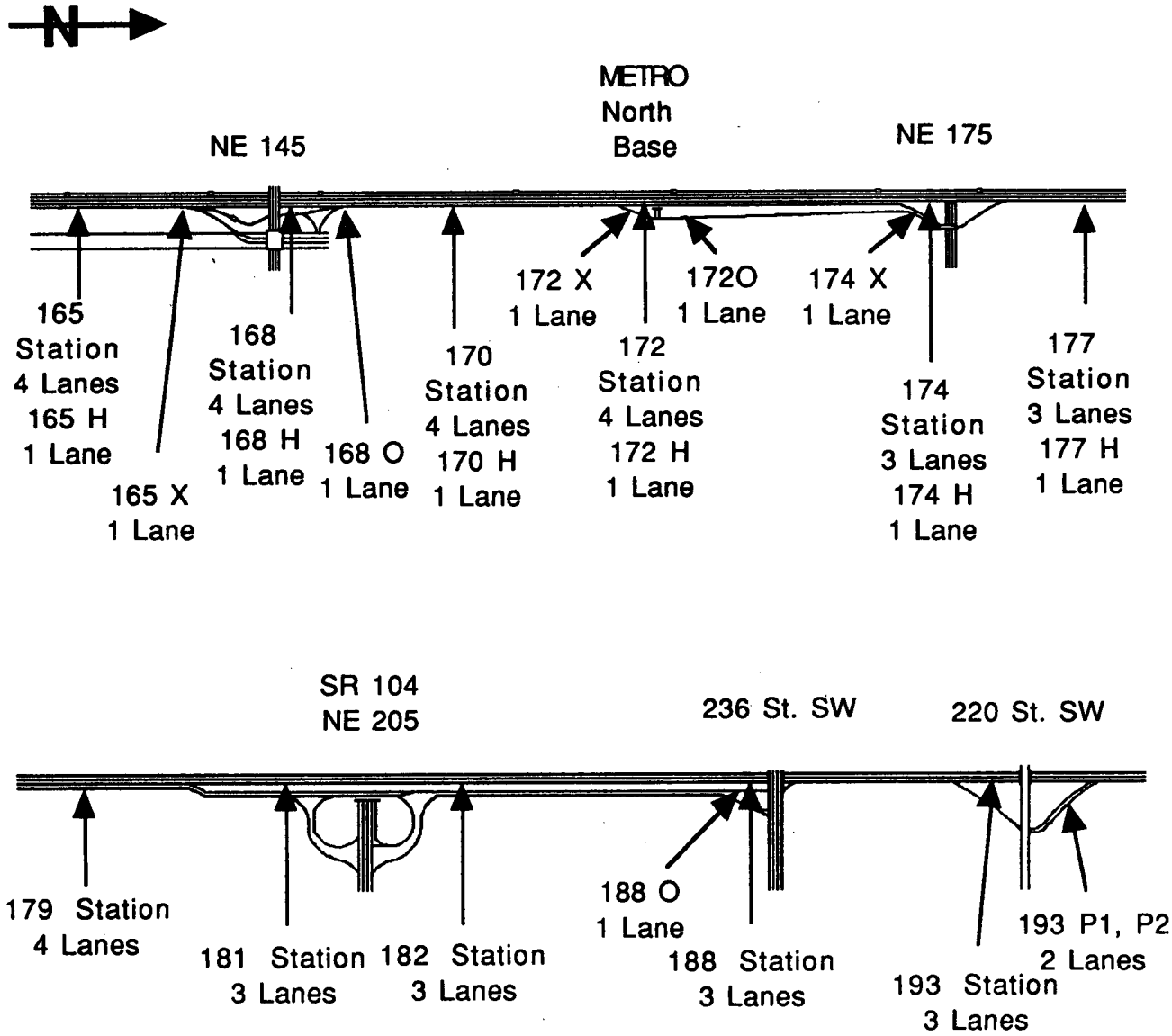
143 X
1 Lane
132 Station
4 Lanes
137
Station
4 Lanes
139
Station
4 Lanes
143
Station
4 Lanes


NE 70
Express Lanes
NE 80
NE 85
146 D
1 Lane
146 Station
3 Lanes
146 X
1 Lane
148 X
1 Lane
148 Station
3 Lanes
151 P
1 Lane
151 Station
3 Lanes

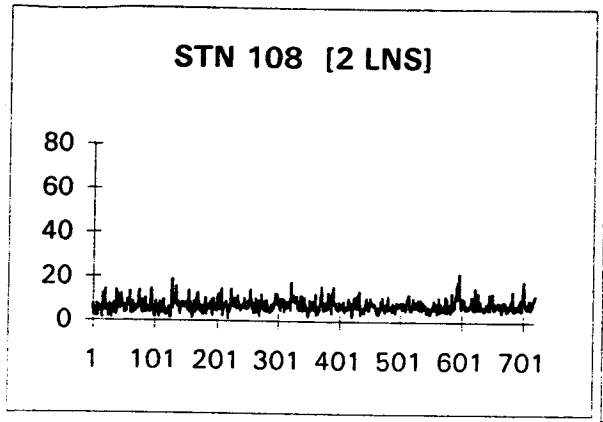

NE Northgate Way
NE 130
154
Station
4 Lanes
156 X1, X2
2 Lanes
156
Station
4 Lanes
156 H
1 Lane
159 Station
4 Lanes
159 H
1 Lane
159 P
1 Lane
161
Station
4 Lanes
161 H
1 Lane
163 X
1 Lane
163
Station
4 Lanes
163 H
1 Lane

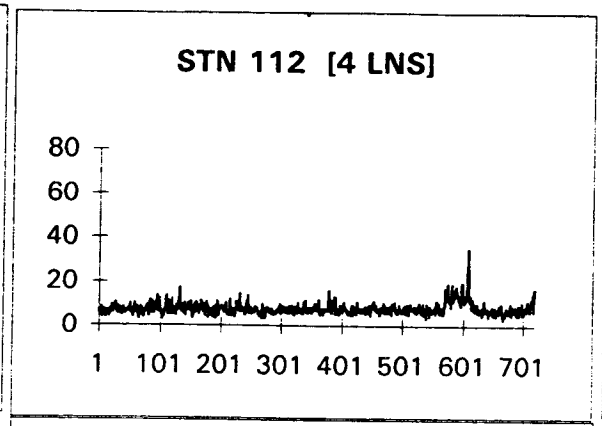

N
METRO
North
Base
NE 145
NE 175
165
Station
4 Lanes
165 H
1 Lane
165 X
1 Lane
168
Station
4 Lanes
168 H
1 Lane
168 O
1 Lane
170
Station
4 Lanes
170 H
1 Lane
172 X
1 Lane
172
Station
4 Lanes
172 H
1 Lane
172O
1 Lane
174 X
1 Lane
174
Station
3 Lanes
174 H
1 Lane
177
Station
3 Lanes
177 H
1 Lane
SR 104
NE 205
236 St. SW
220 St. SW
179 Station
4 Lanes
181 Station
3 Lanes
182 Station
3 Lanes
188 O
1 Lane
188 Station
3 Lanes
193 Station
3 Lanes
193 P1, P2
2 Lanes

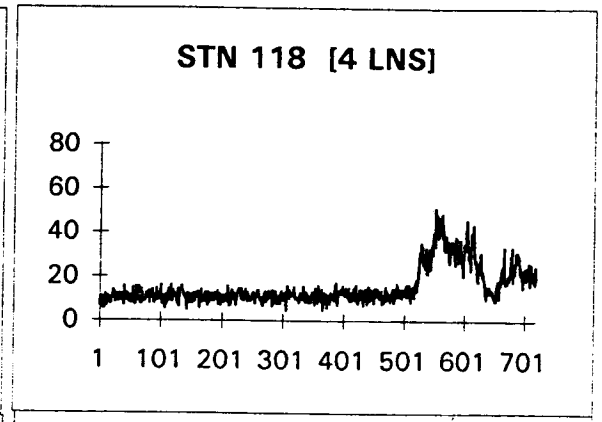
APPENDIX B: GRAPHS OF DATA FOR NOVEMBER 10, 1993

(STATIONS 108-168)

Occupancy vs Time Interval (Stations)

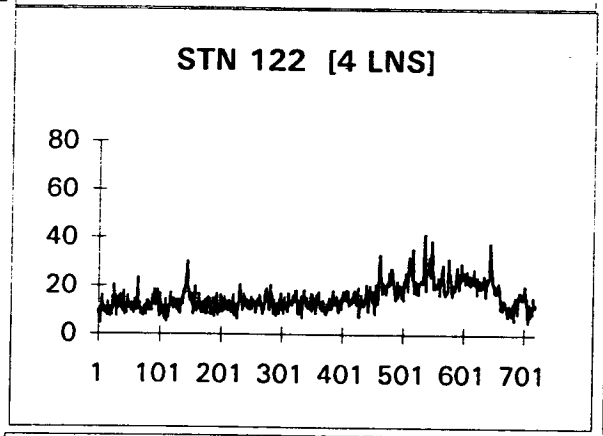


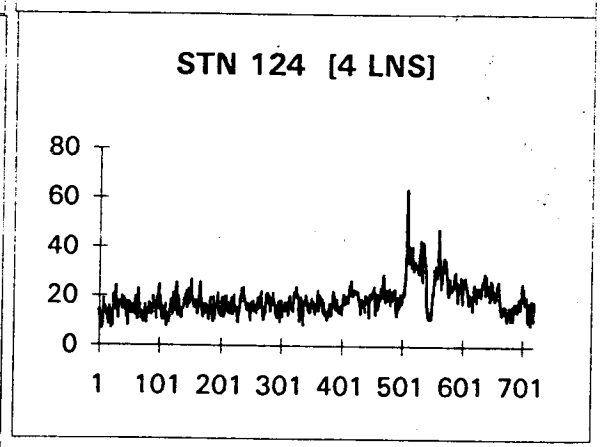


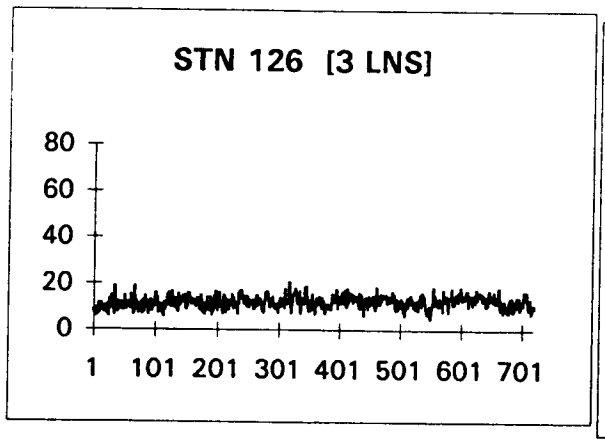


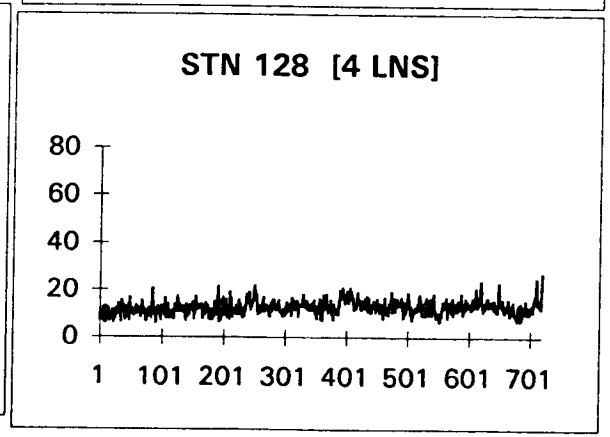
STN 120

BAD OCCUPANCY DATA







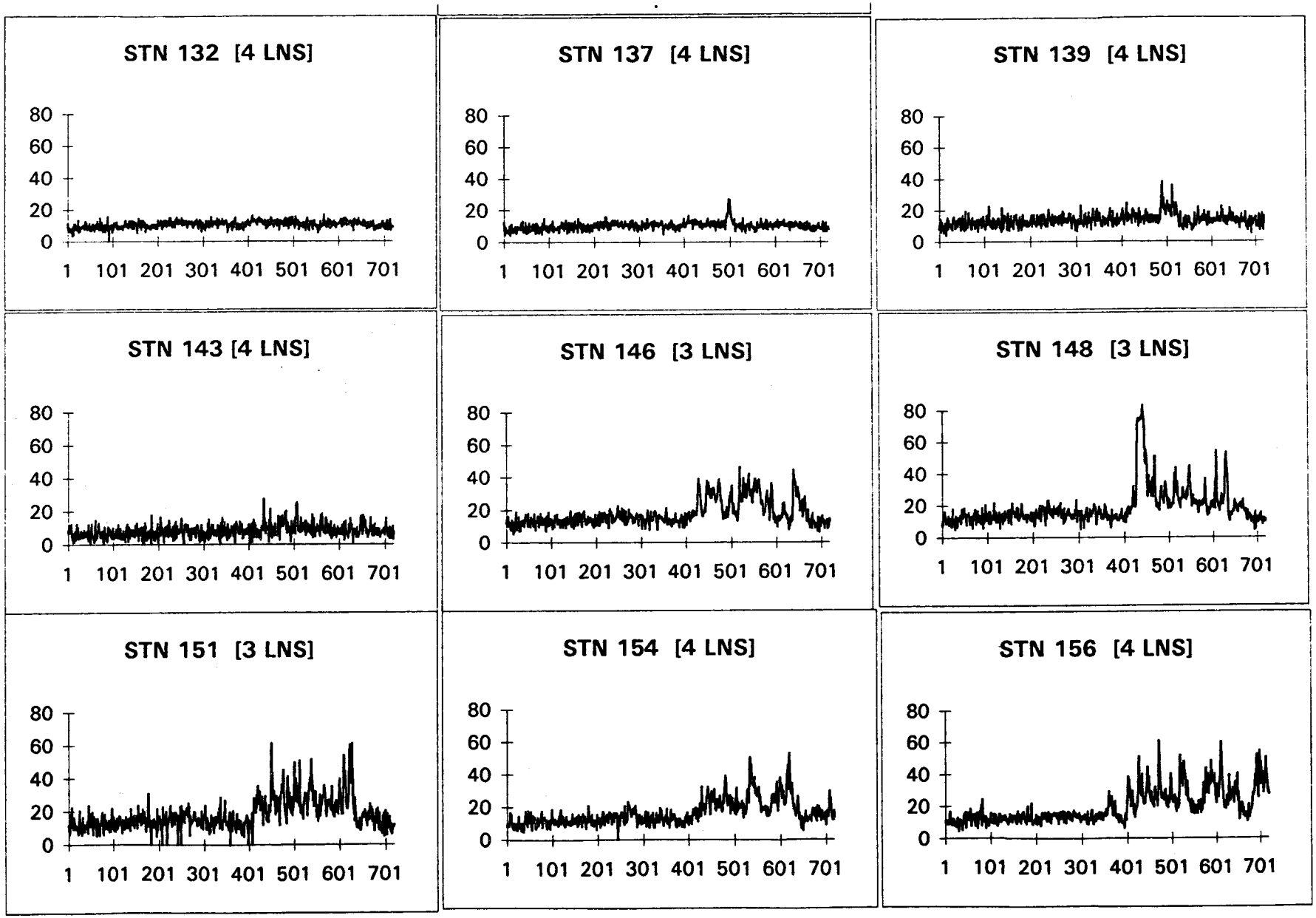


STN 130

BAD DATA

Date of Collection: 11/10/93

Occupancy vs Time Interval (Stations)



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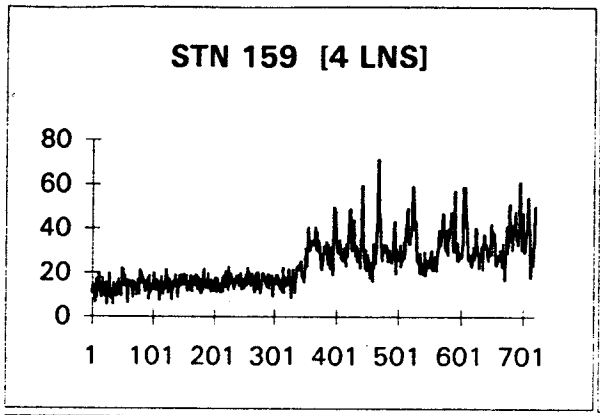
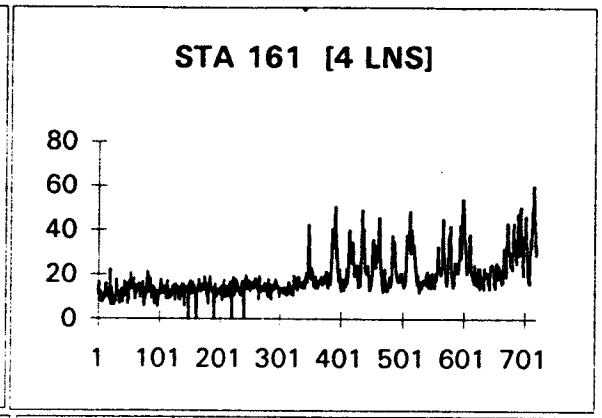
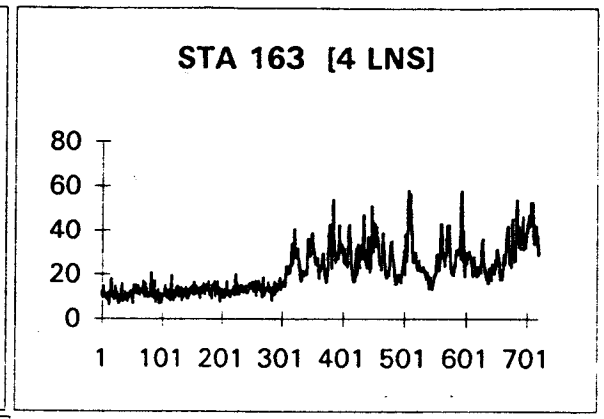
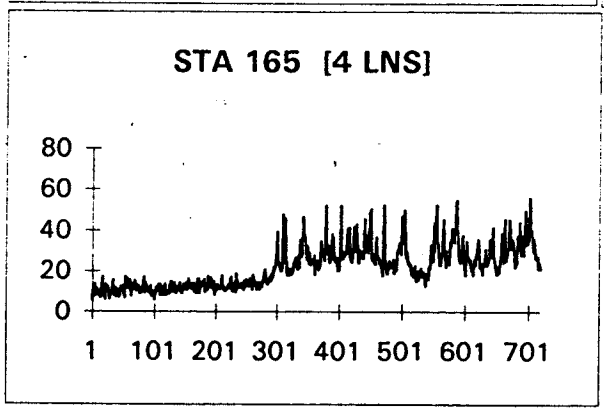
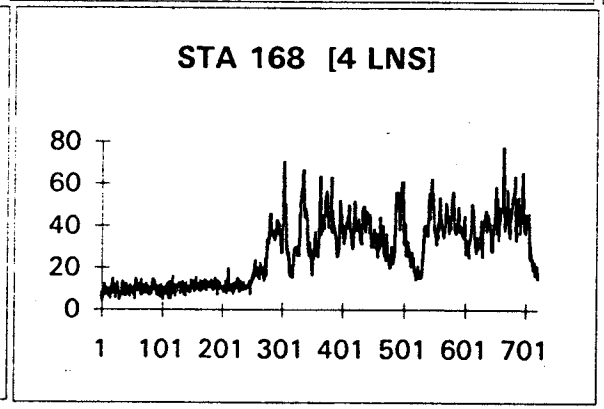
Occupancy vs Time Interval (Stations)





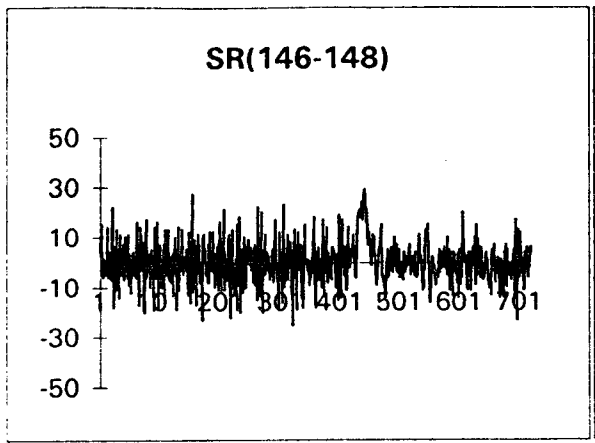


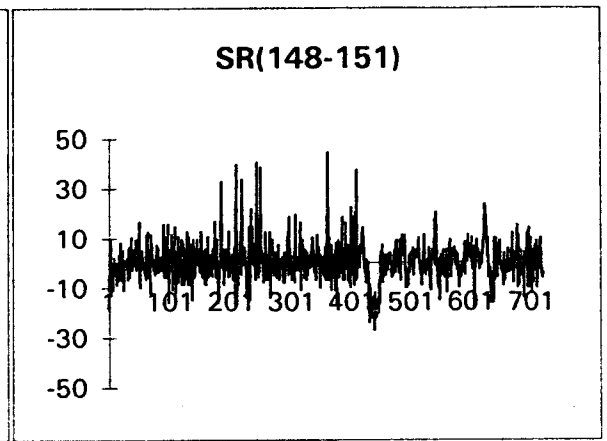




Date of Collection: 11/10/93

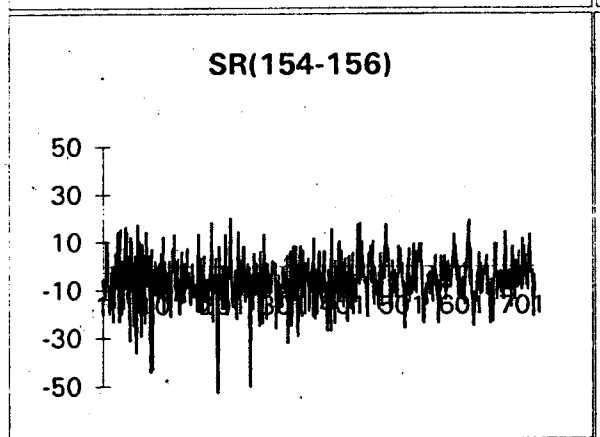
Storage Rate vs Time Interval

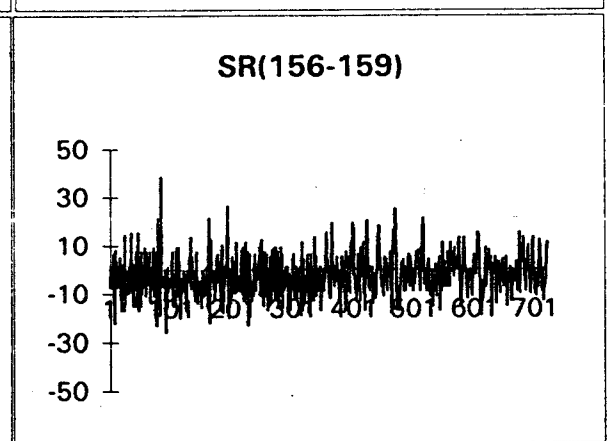




SR(151-154)

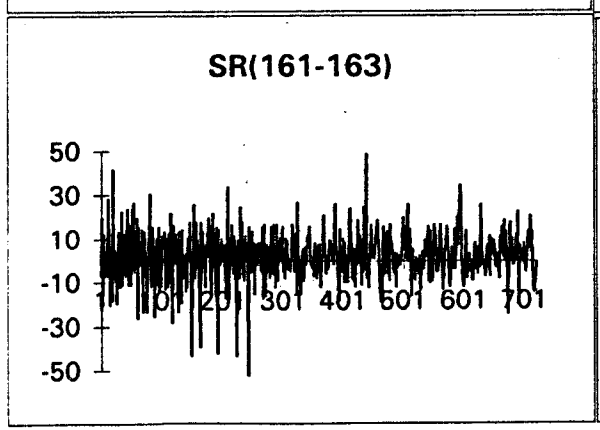
NO DATA FOR 151 P

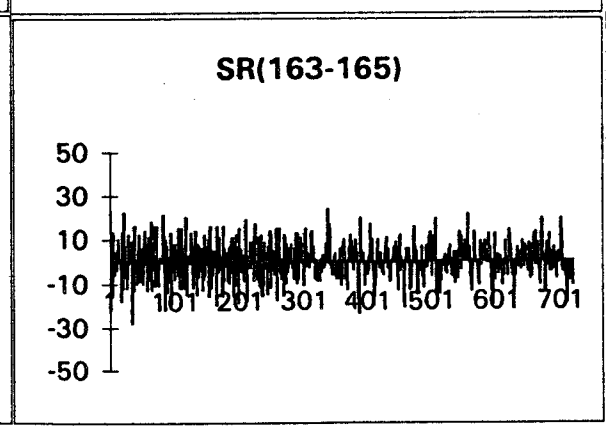


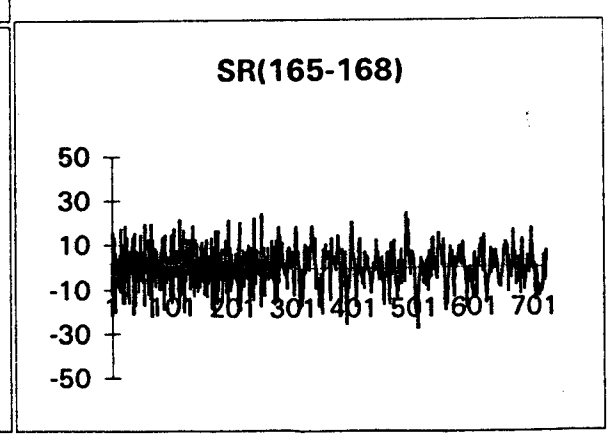


SR(159-161)

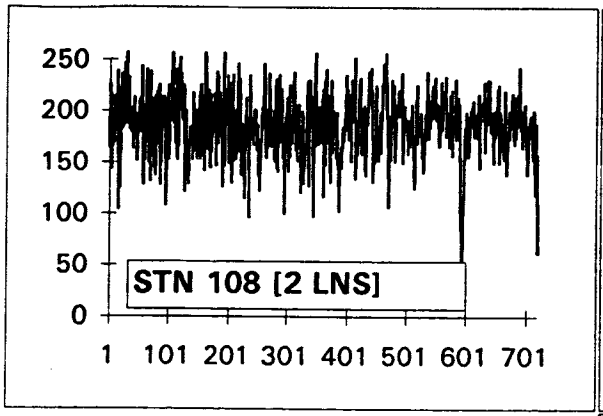
NO DATA FOR 159 P

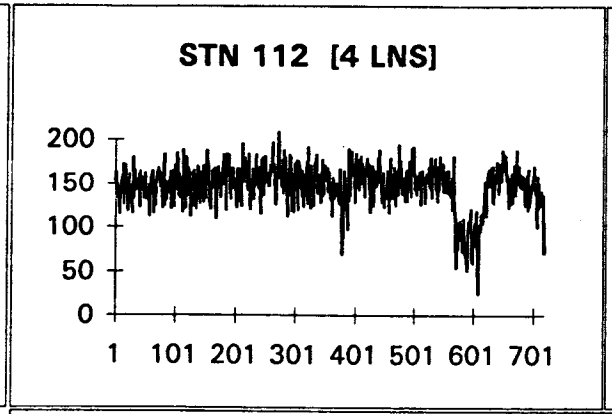


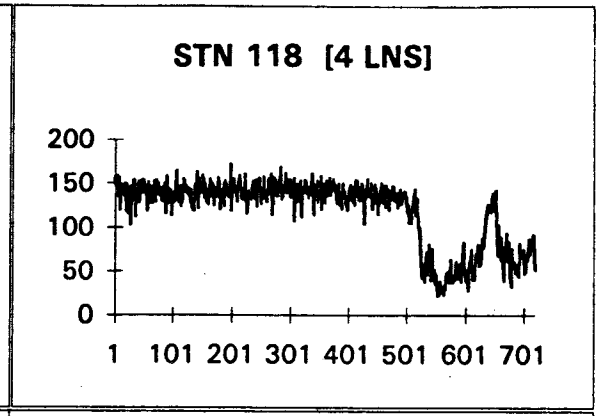




Flow/Occupancy Ratio vs Time Interval

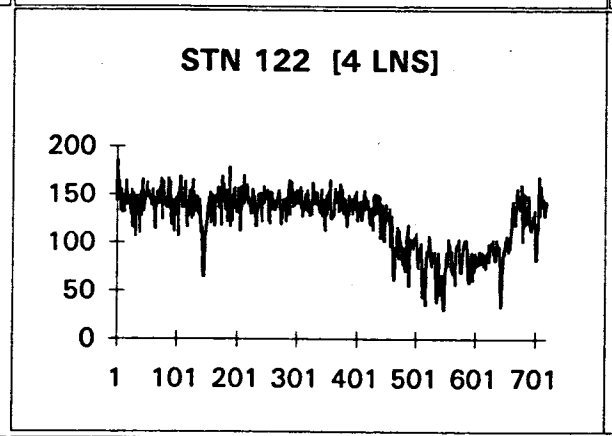


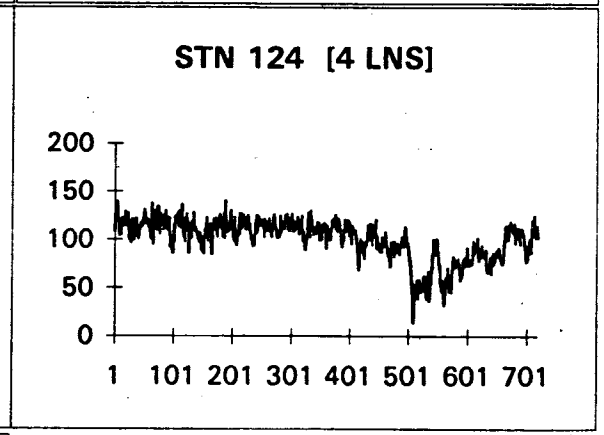


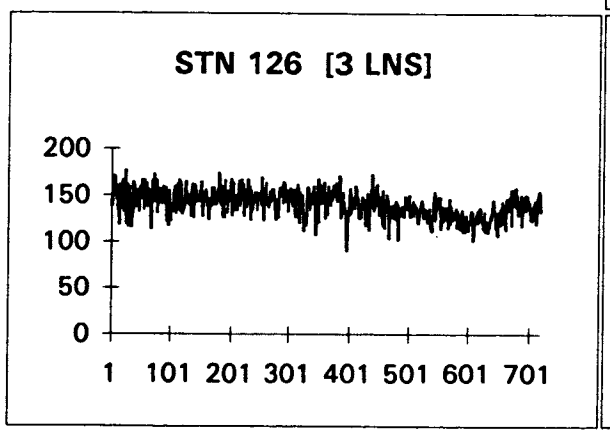


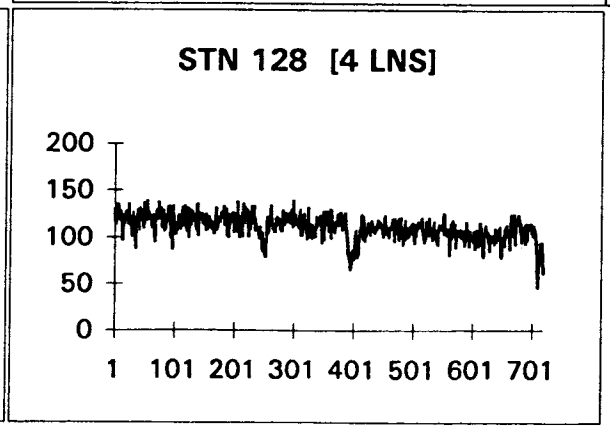
STN 120

BAD OCCUPANCY DATA







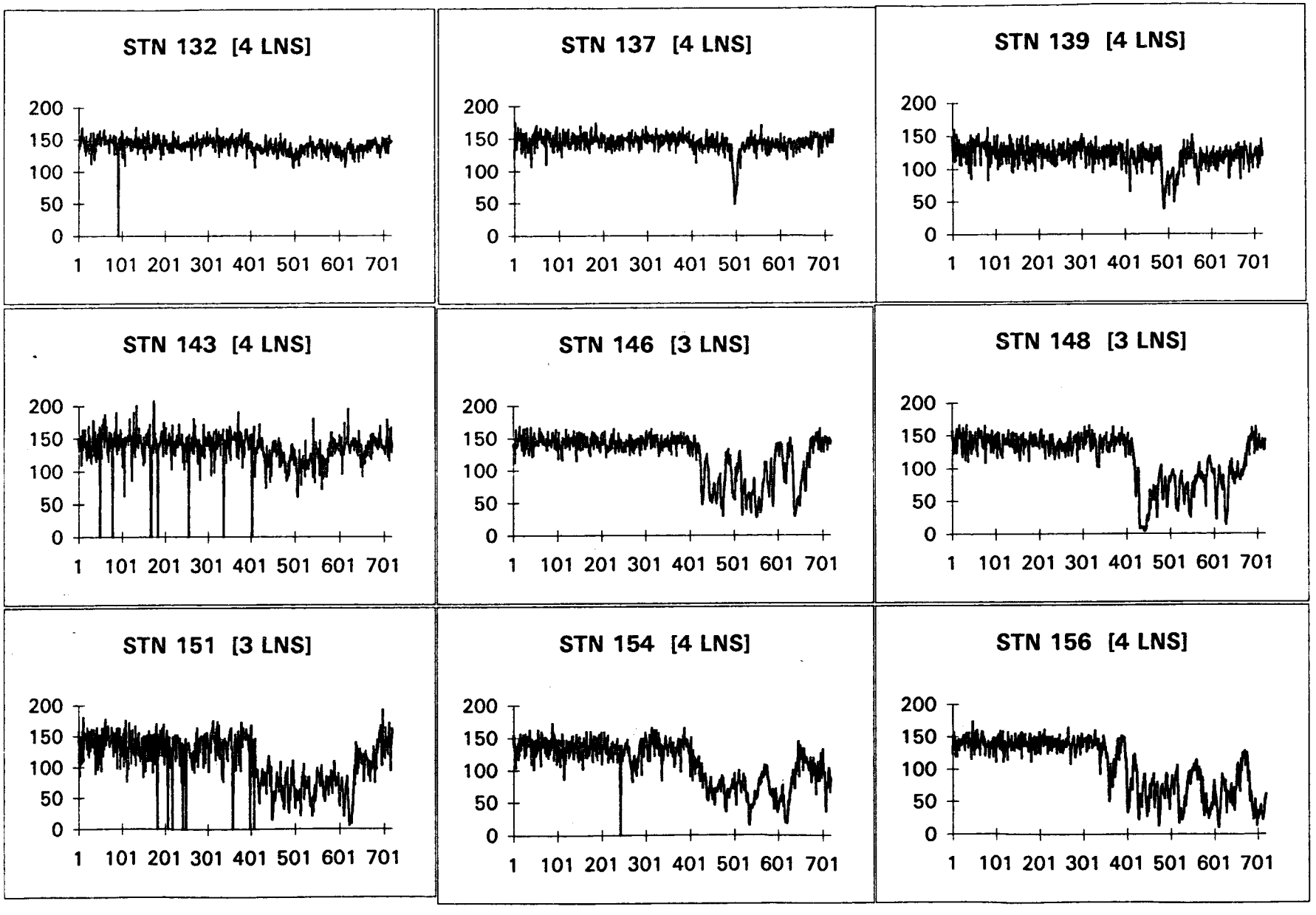


STN 130

BAD DATA

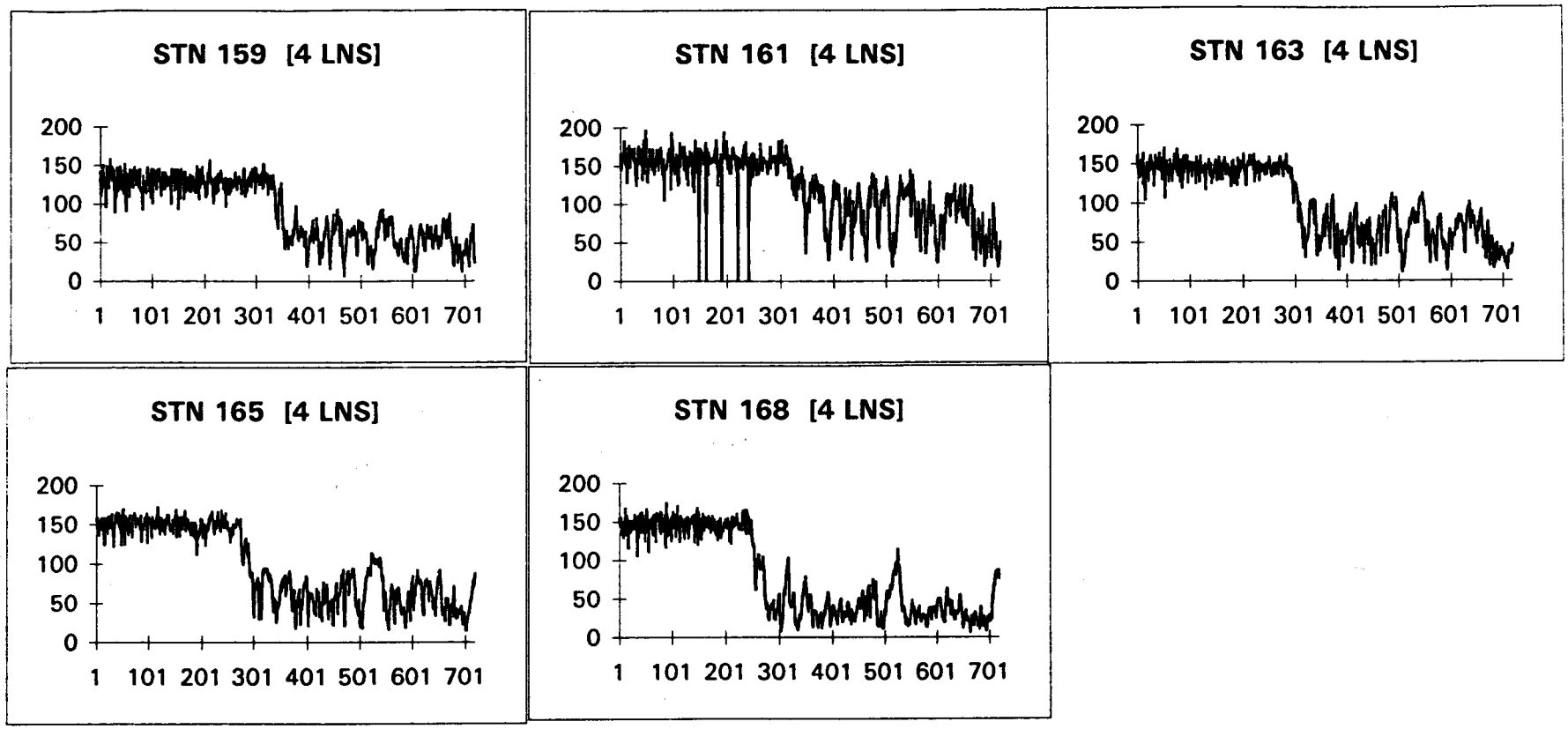
Date of Collection: 11/10/93

Flow/Occupancy Ratio vs Time Interval



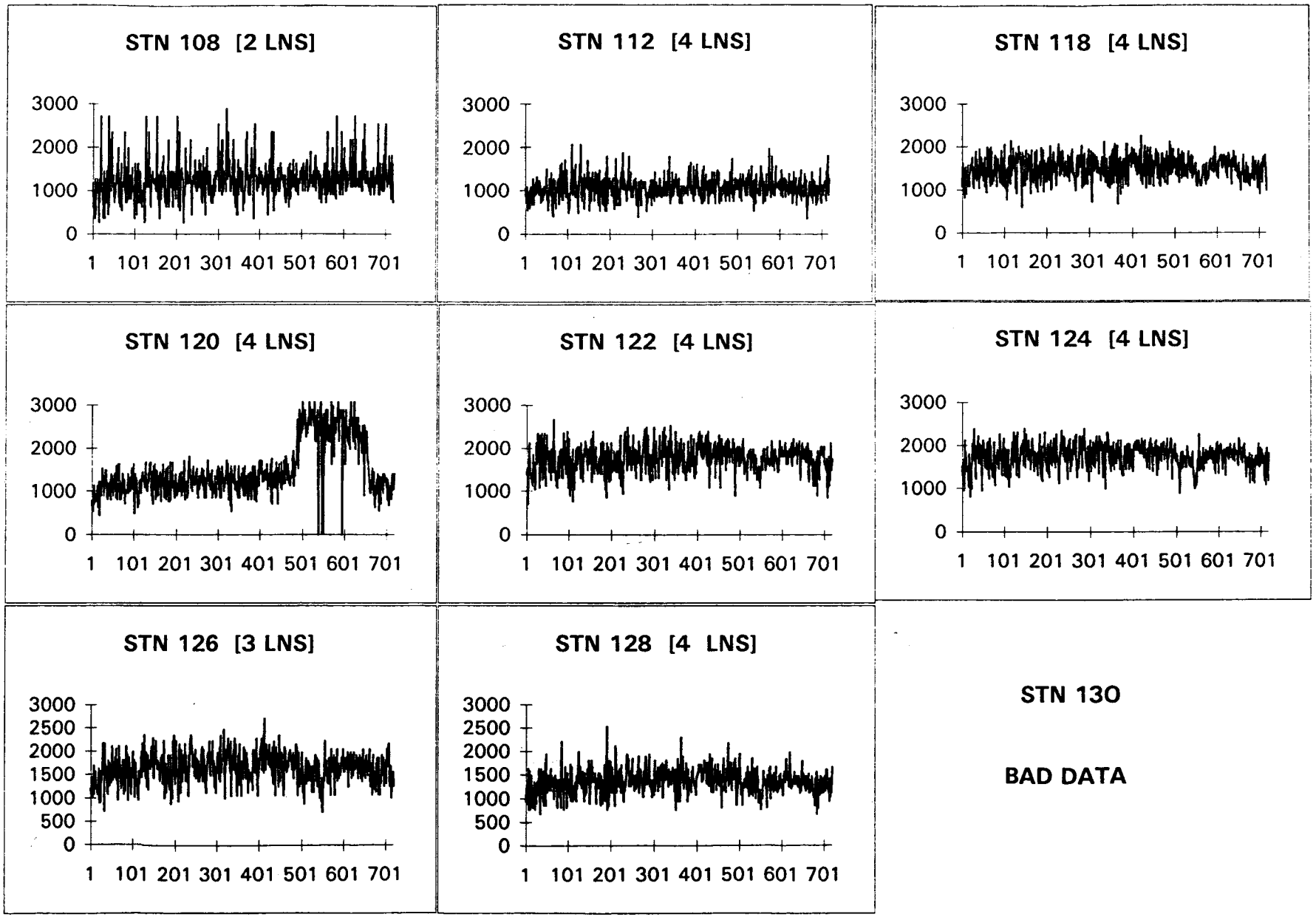
Date of Collection: 11/10/93

Flow/Occupancy Ratio vs Time Interval



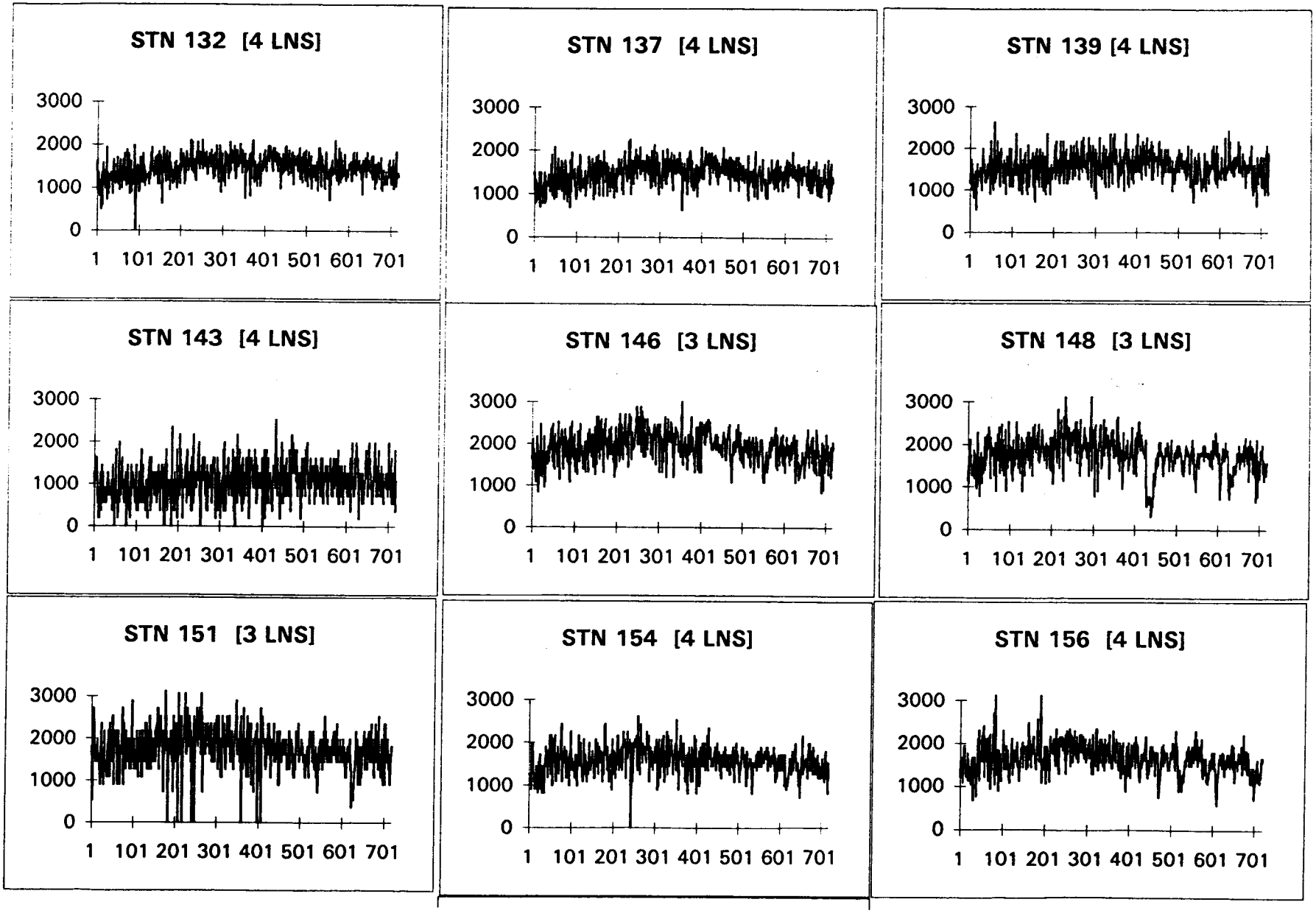
Date of Collection: 11/10/93

Flow Rate vs Time Interval



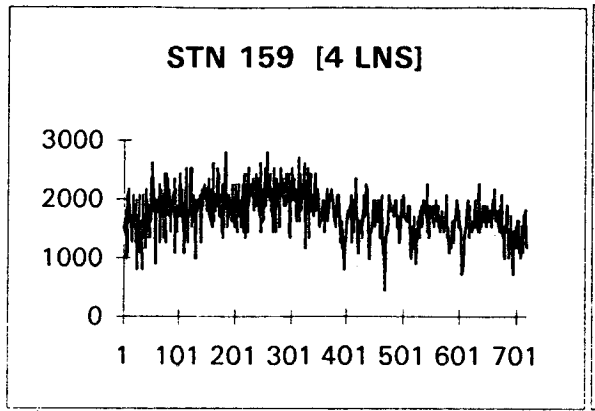
Date of Collection: 11/10/93

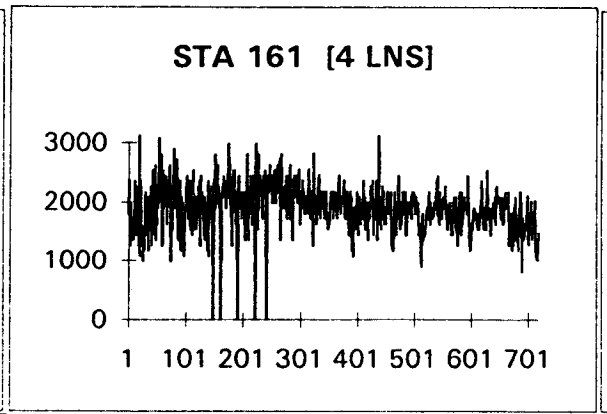
Flow Rate vs Time Interval

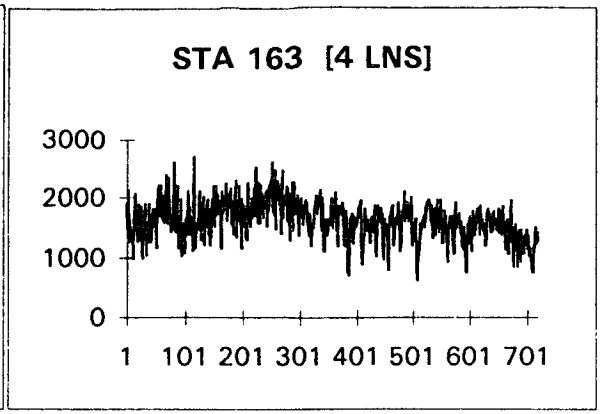


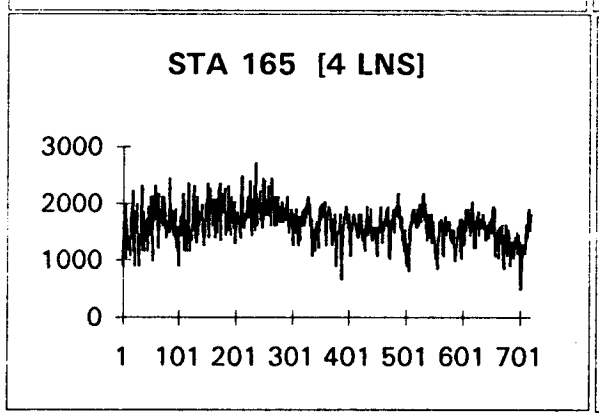
Date of Collection: 11/10/93

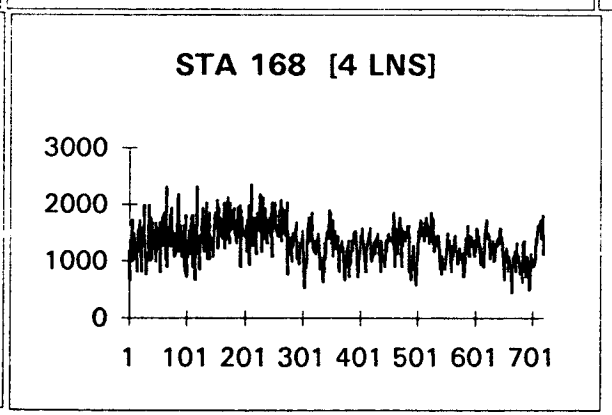
Flow Rate vs Time Interval









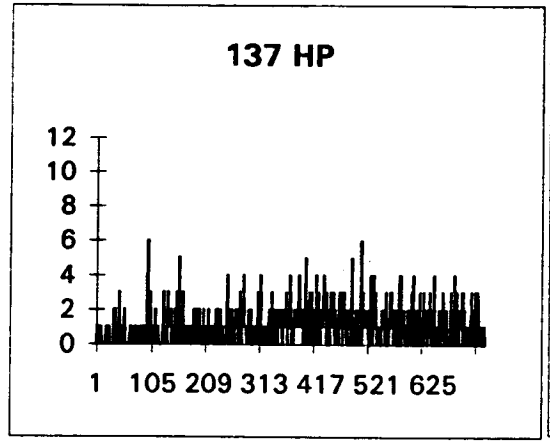


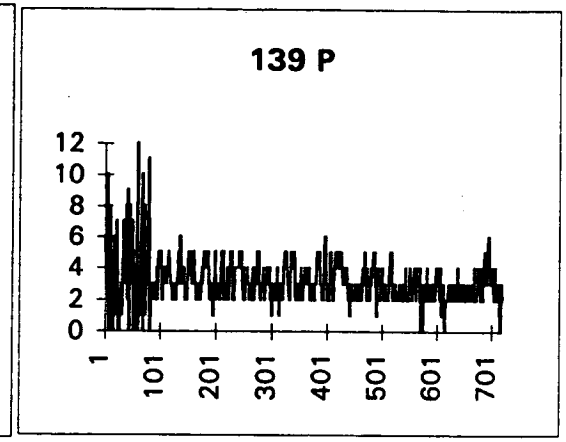
Date of Collection: 11/10/93

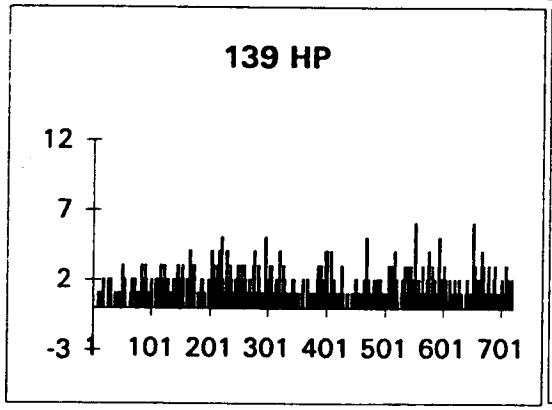
Metered Volume vs Time Interval

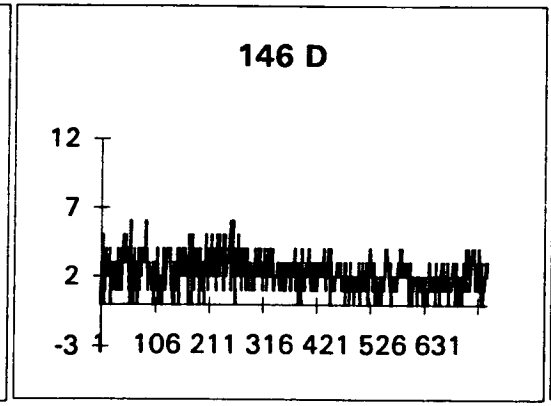
137 P

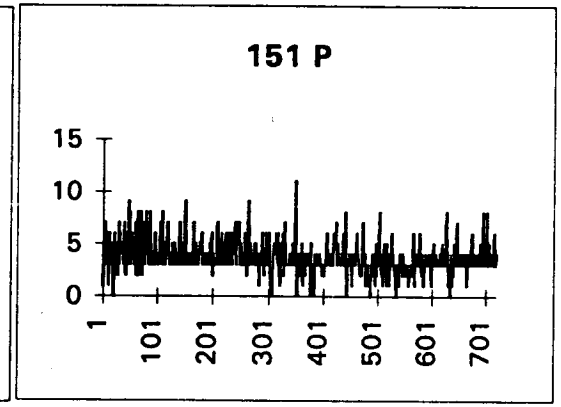
NO DATA











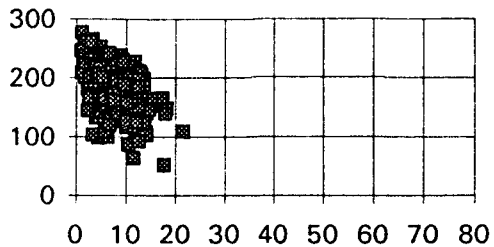
159 P

NO DATA

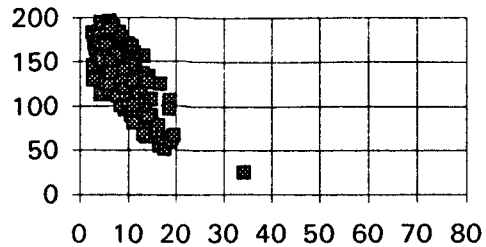
Date of Collection: 11/10/93

Flow/Occupancy Ratio vs Occupancy

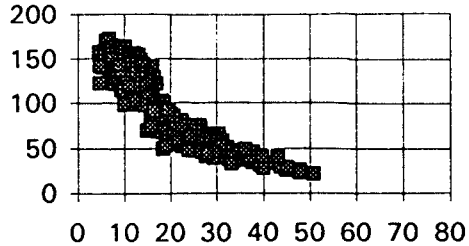
STN 108 [2]



STN 112



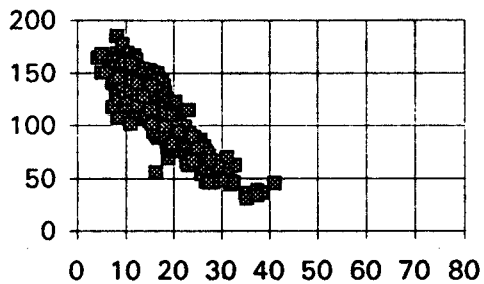
STN 118



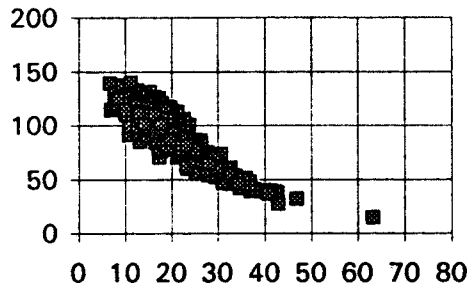
STN 120

BAD OCCUPANCY DATA

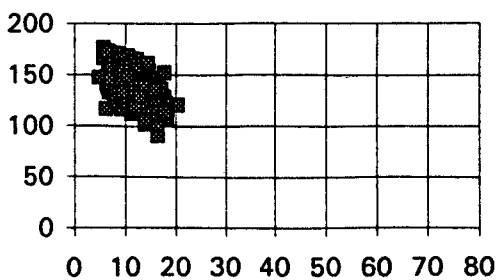
STN 122



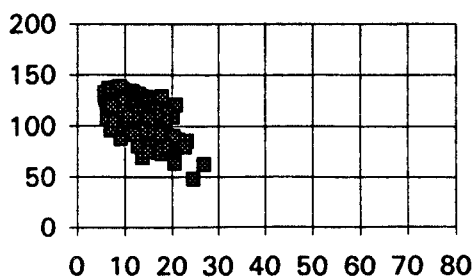
STN 124



STN 126 [3]



STN 128

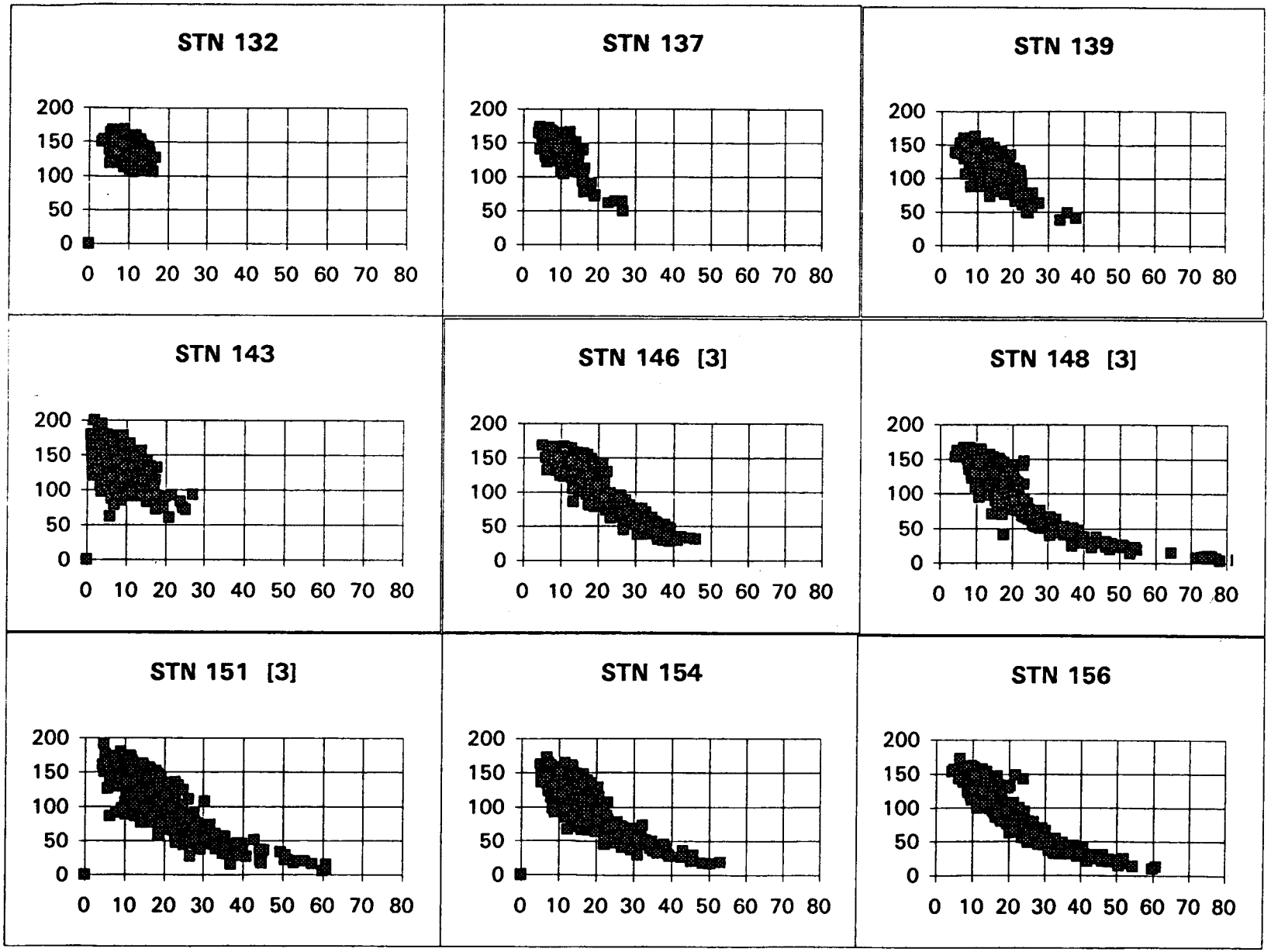


STN 130

BAD DATA

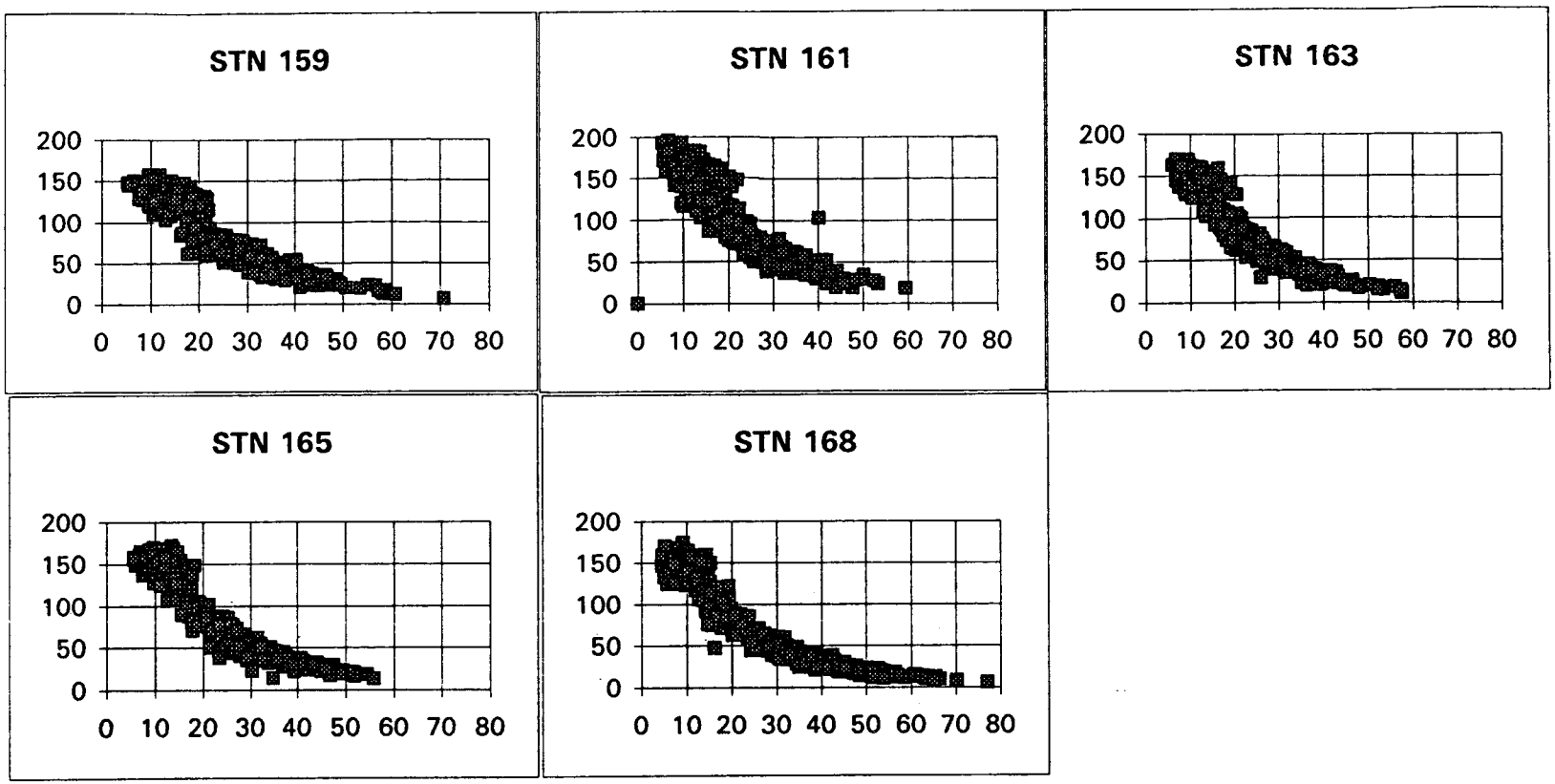
Date of Collection: 11/10/93

Flow/Occupancy Ratio vs Occupancy



Date of Collection: 11/10/93

Flow/Occupancy Ratio vs Occupancy

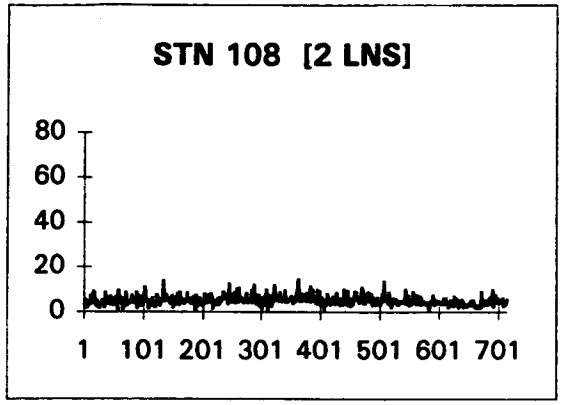


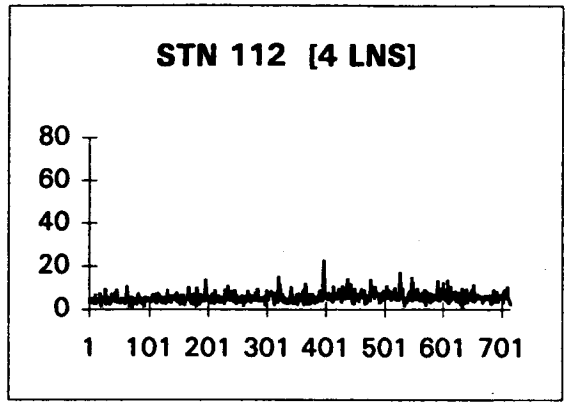
Date of Collection: 11/10/93

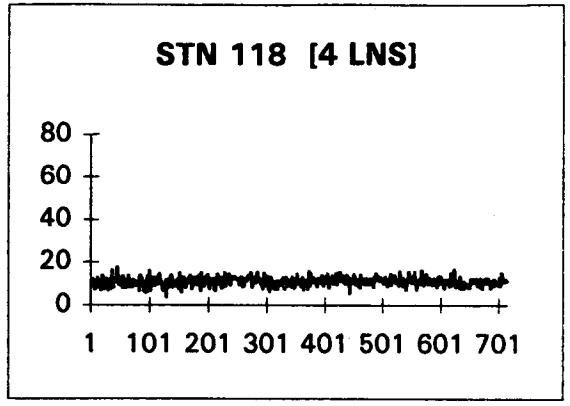
APPENDIX C: GRAPHS OF DATA FOR DECEMBER 15, 1993

(STATIONS 108-193)

Occupancy vs Time Interval (Station)

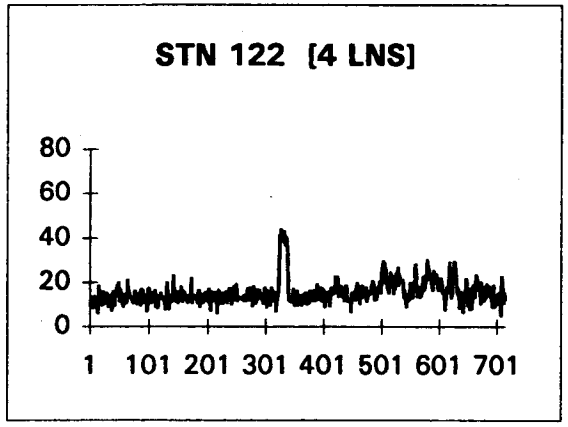


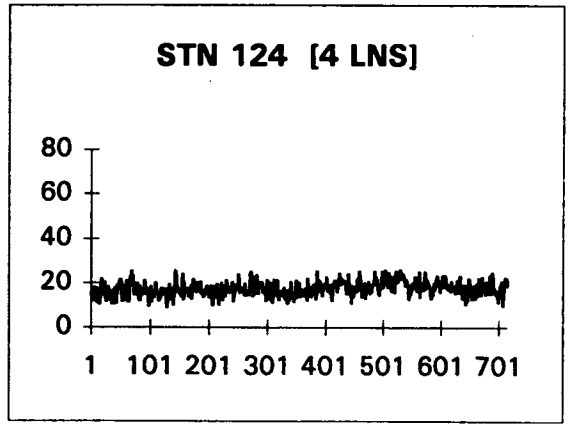


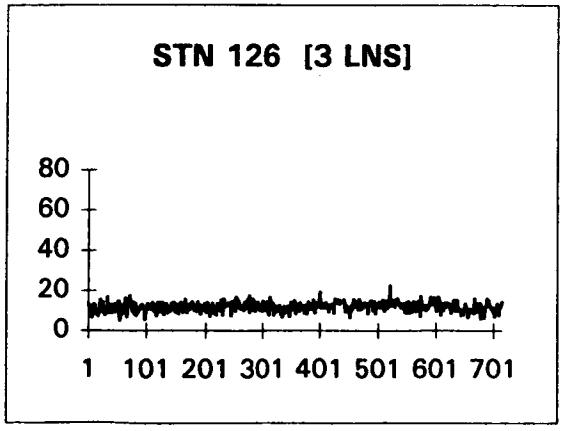


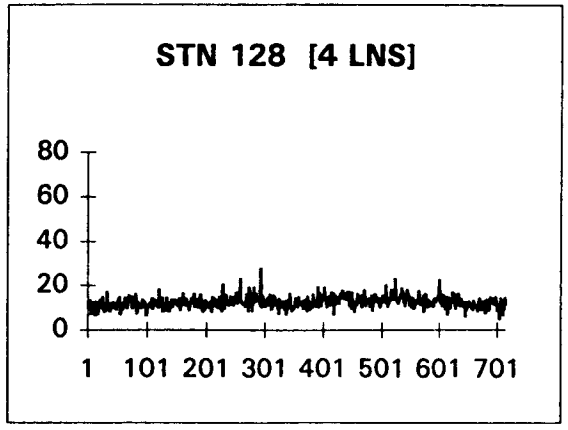
STN 120

BAD OCCUPANCY DATA







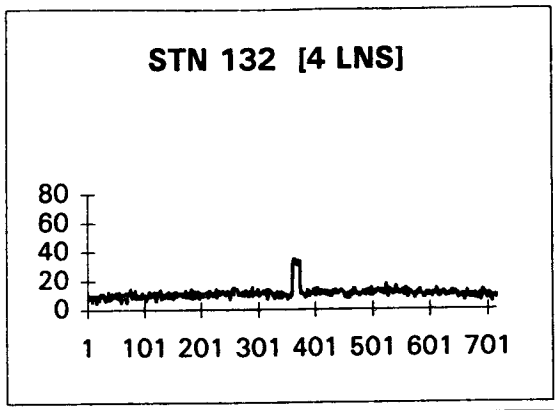


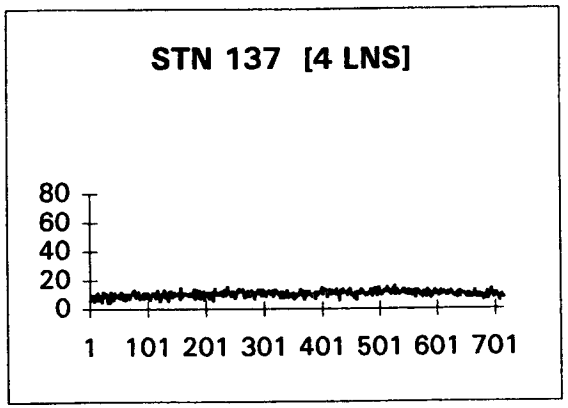
STN 130

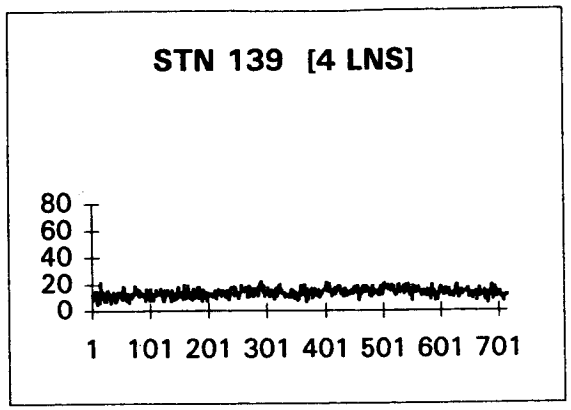
BAD OCCUPANCY DATA

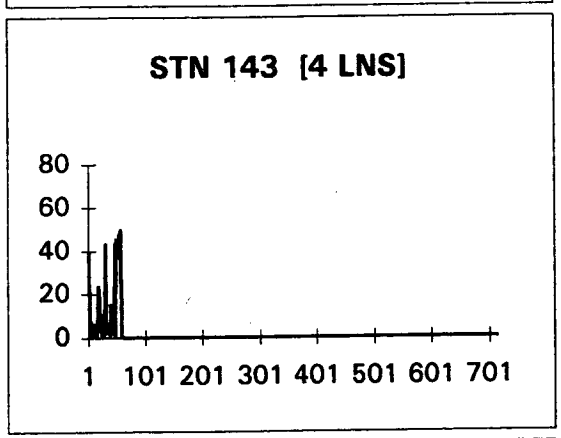
Date of Collection: 12/15/93

Occupancy vs Time Interval (Station)



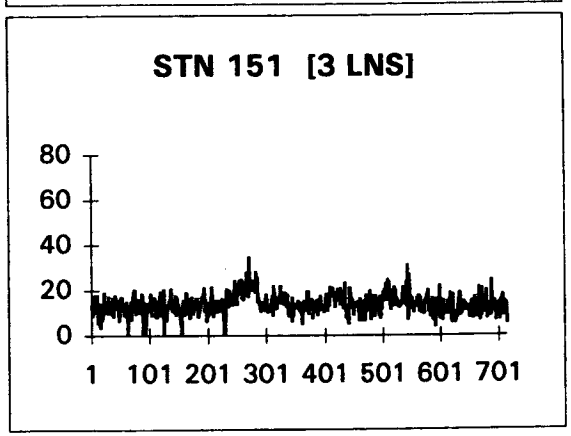


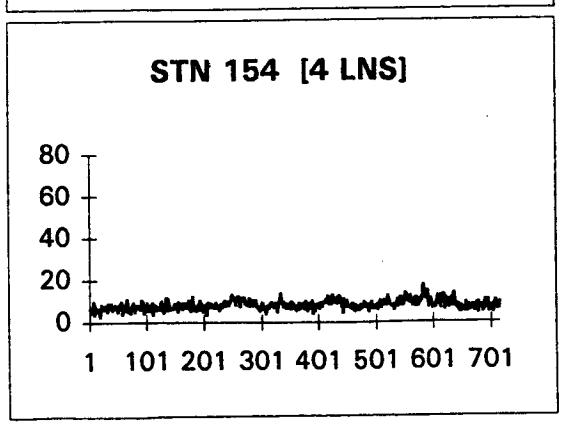




STN 146

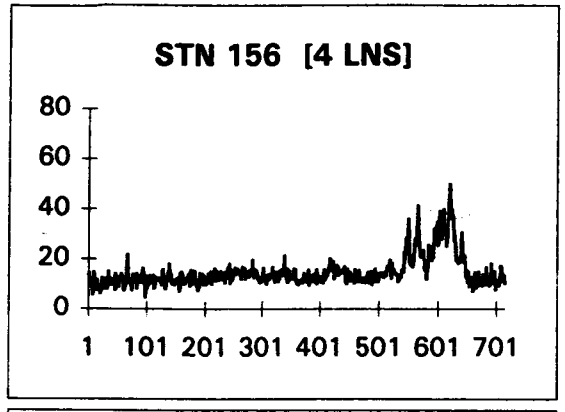
BAD OCCUPANCY DATA

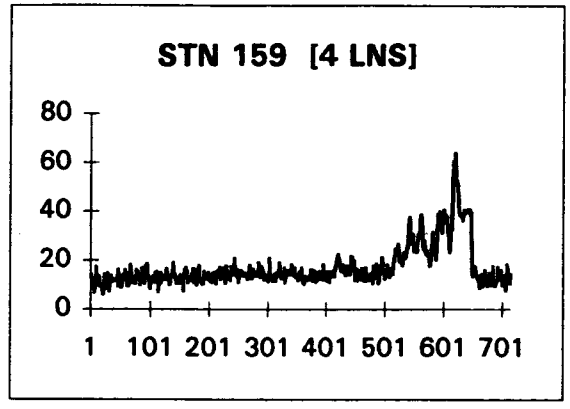


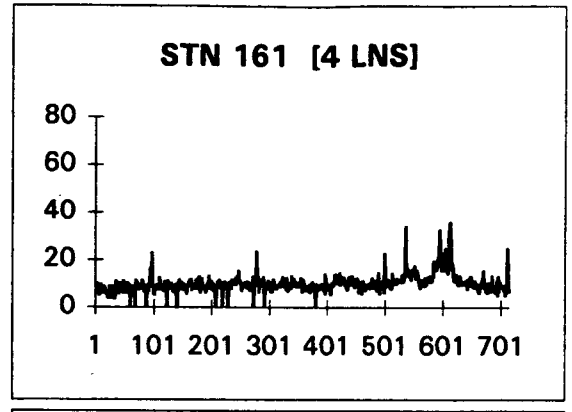


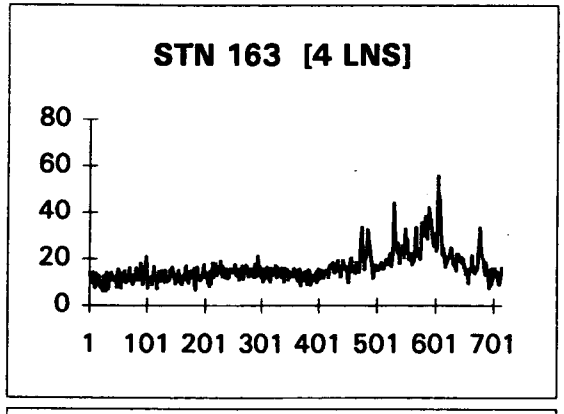
Date of Collection: 12/15/93

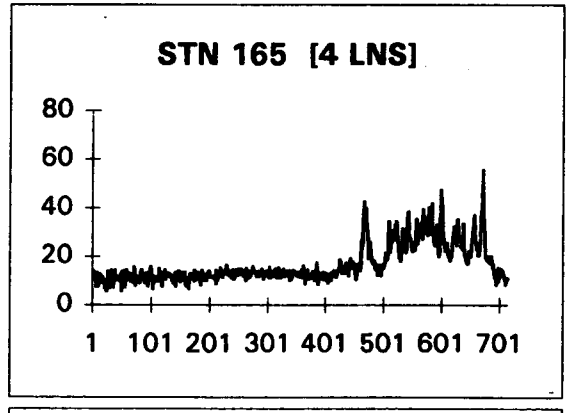
Occupancy vs Time Interval (Stations)

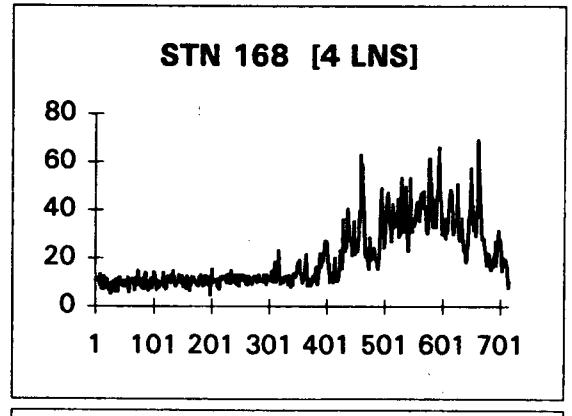


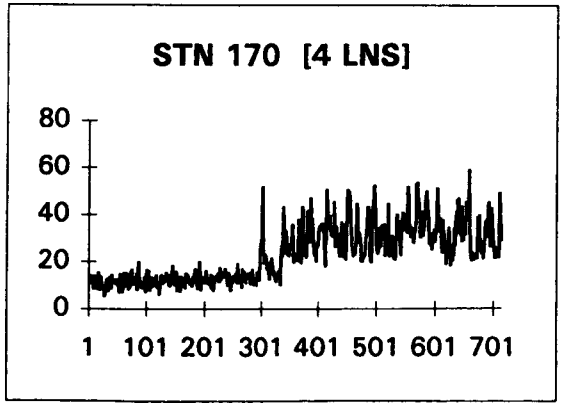


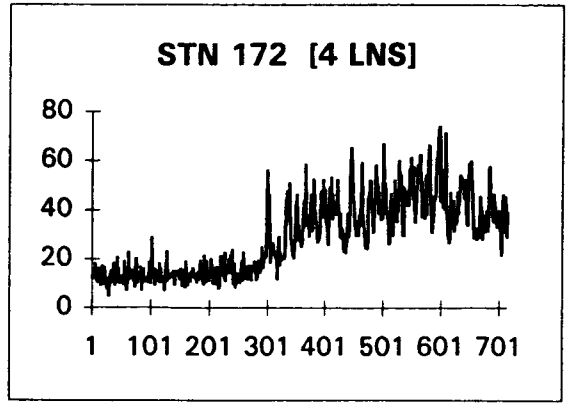


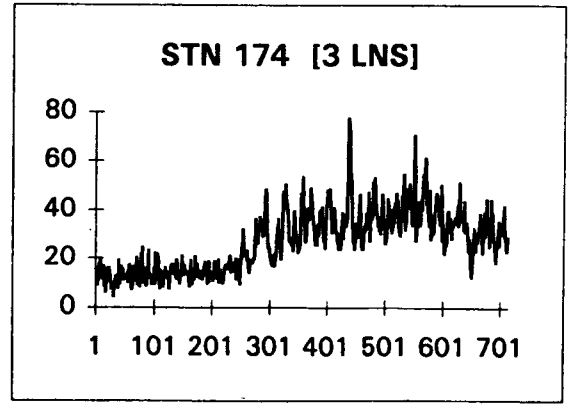






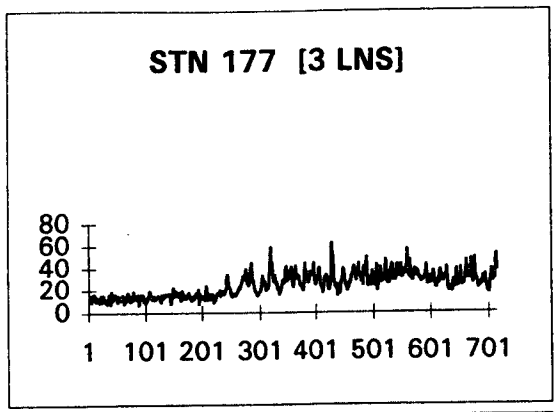


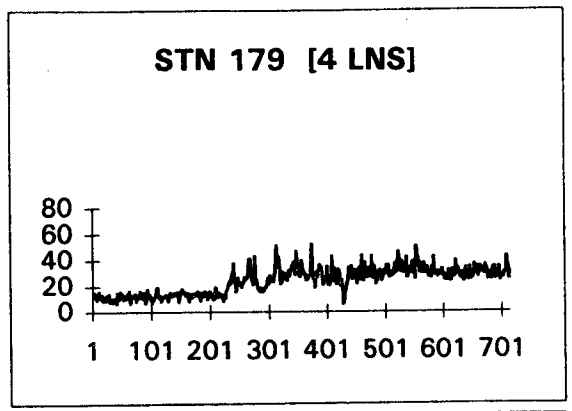


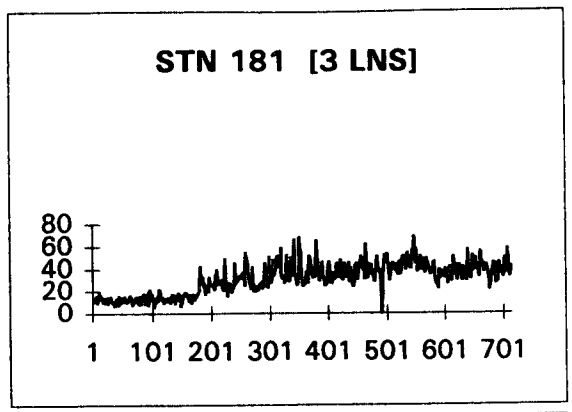


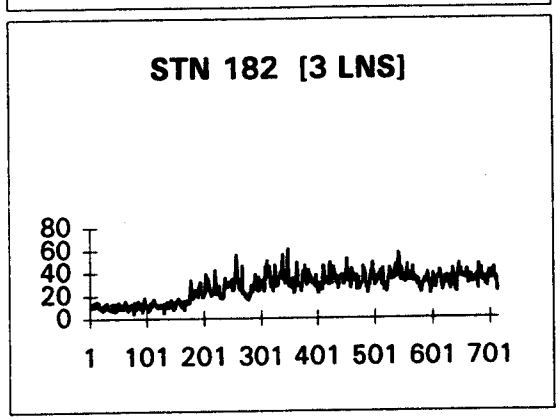
Date of Collection: 12/15/93

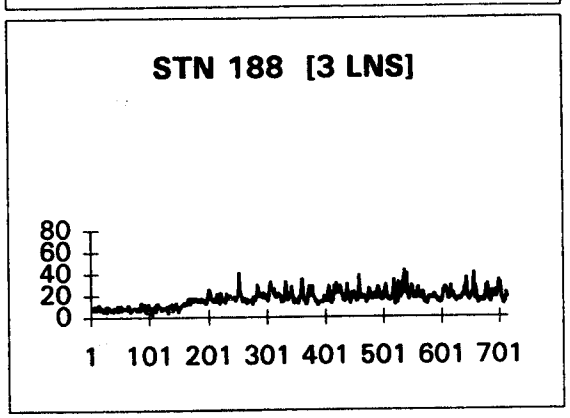
Occupancy vs Time Interval (Stations)

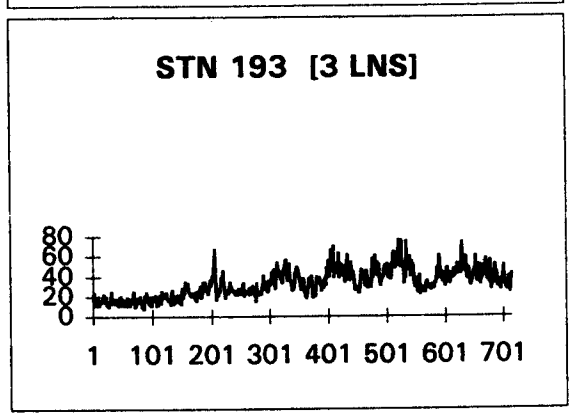










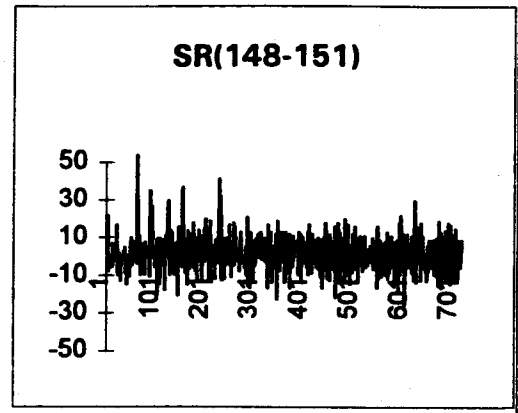


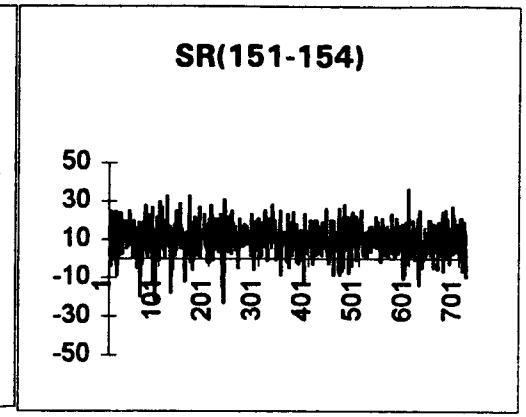
Date of Collection: 12/15/93

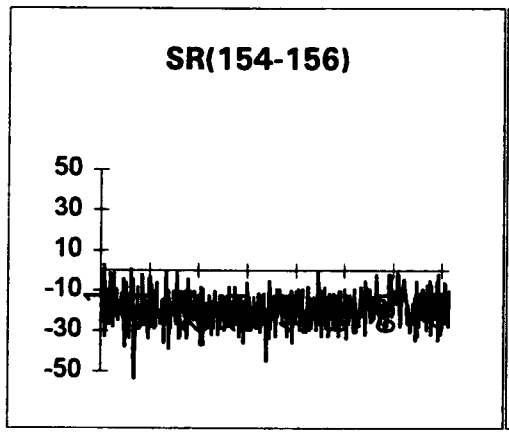
Storage Rate vs Time Interval

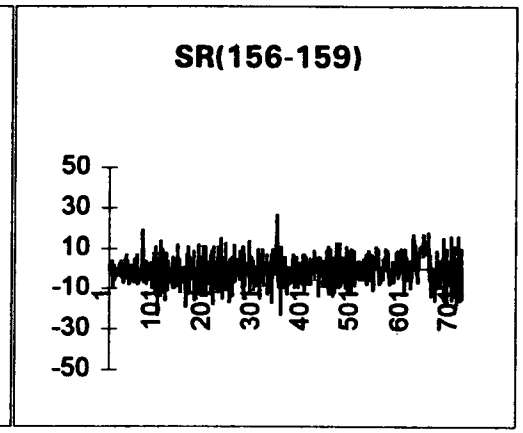
SR(146-148)

NO DATA FOR 146 STN



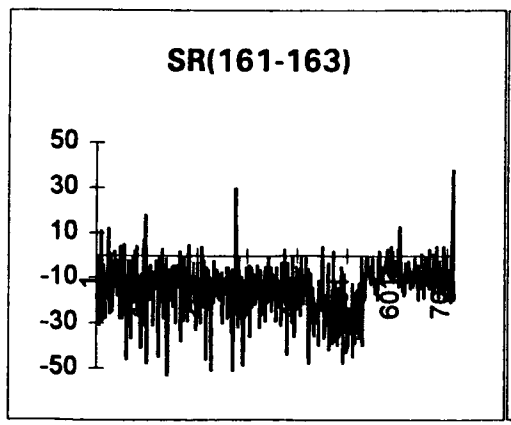


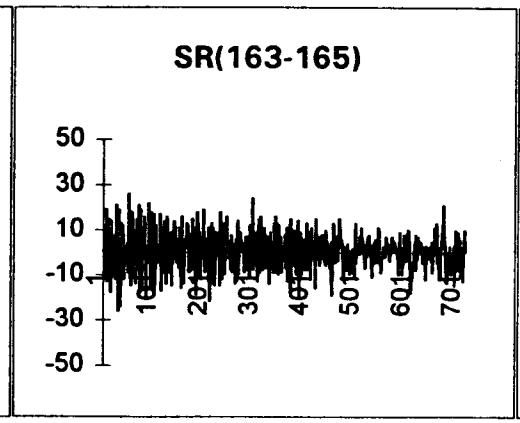


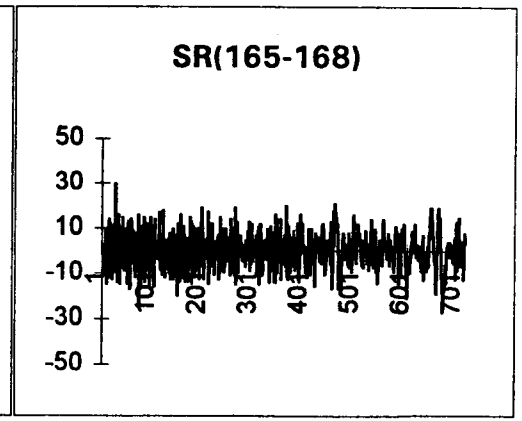


SR(159-161)

NO DATA FOR 159 P

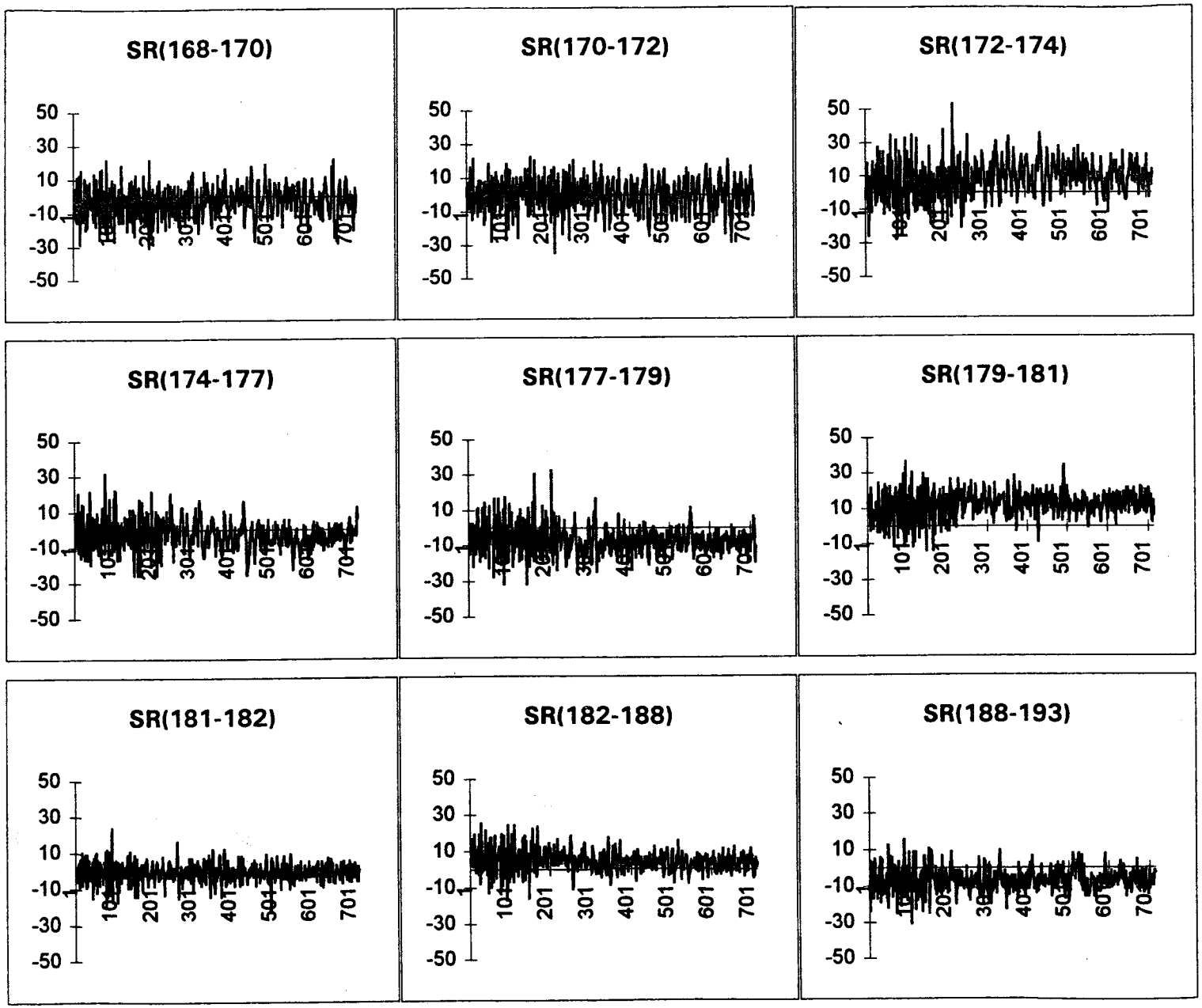






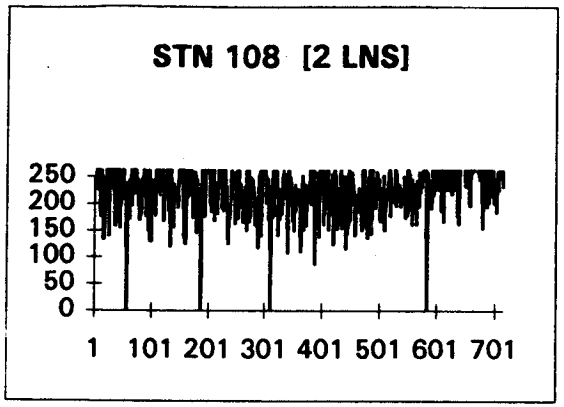
Date of Collection: 12/15/93

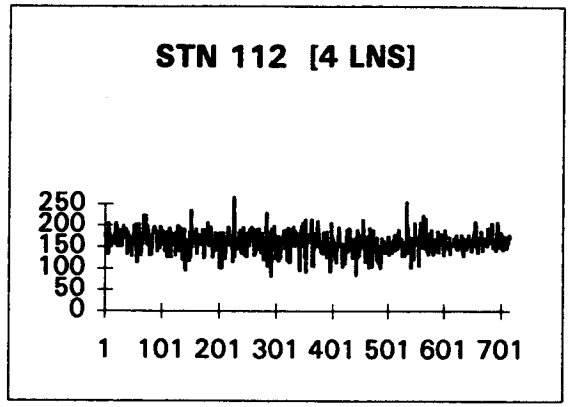
Storage Rate vs Time Interval

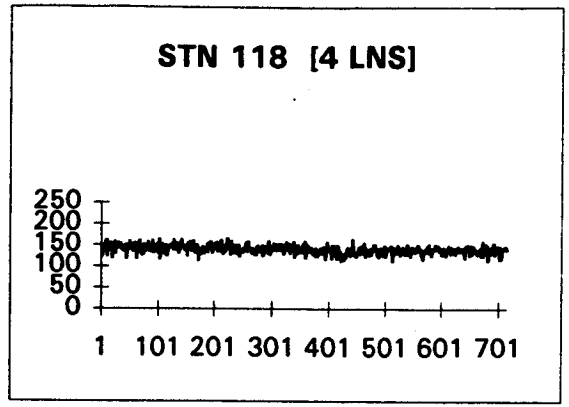


Date of Collection: 12/15/93

Flow/Occupancy Ratio vs Time Interval

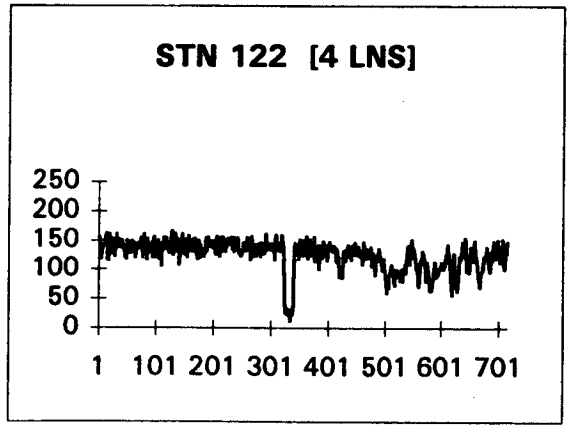


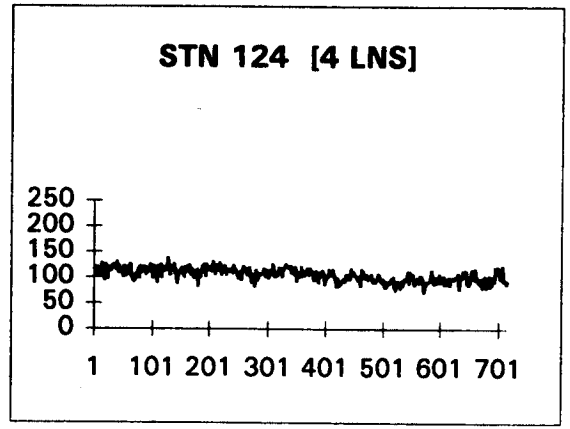


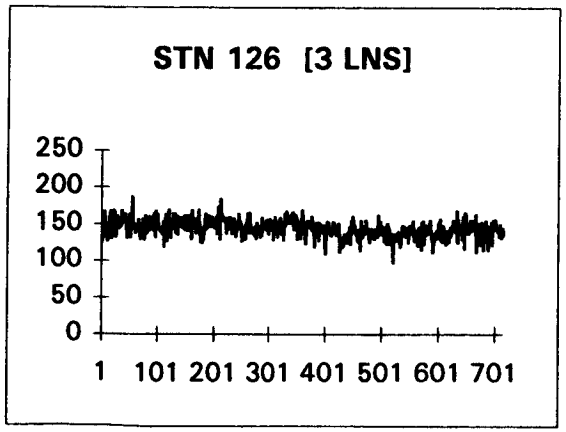


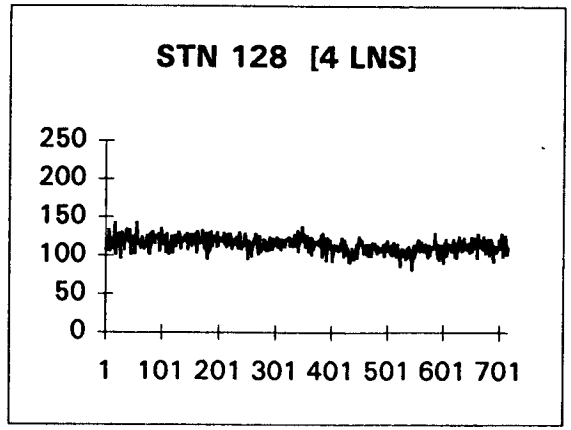
STN 120

BAD DATA







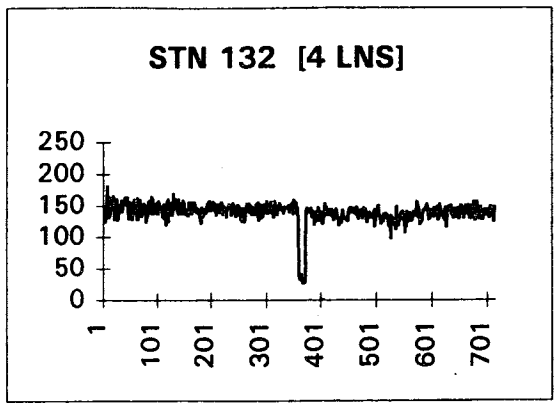


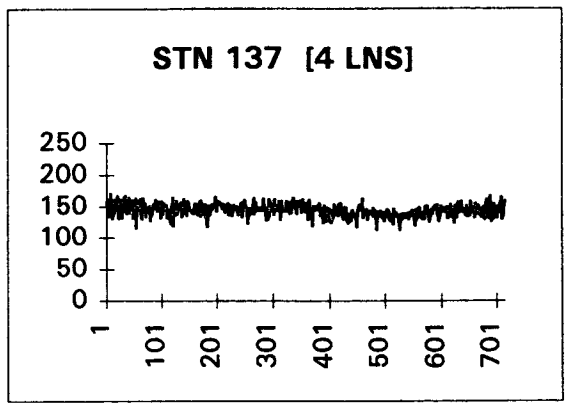
STN 130

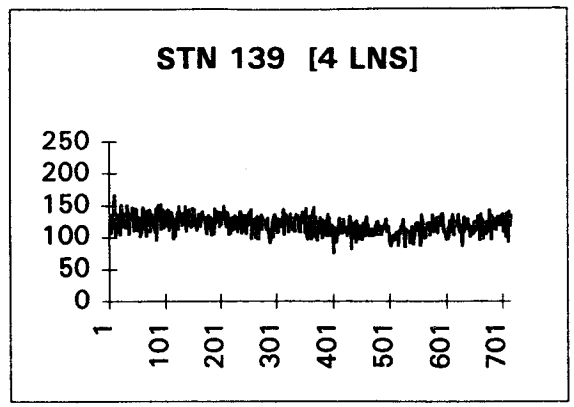
BAD DATA

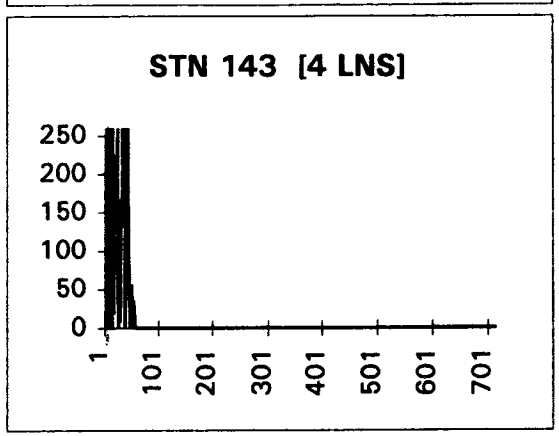
Date of Collection: 12/15/93

Flow/Occupancy Ratio vs Time Interval



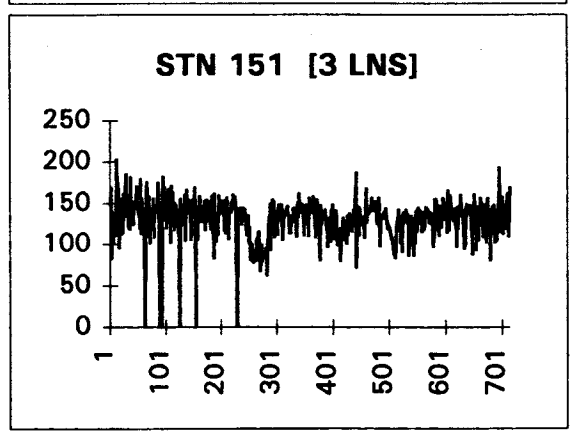


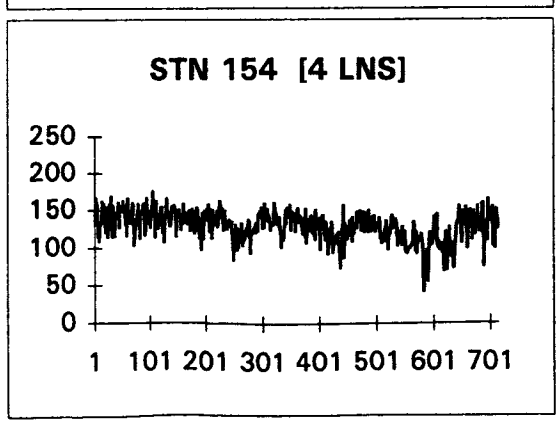




STN 146

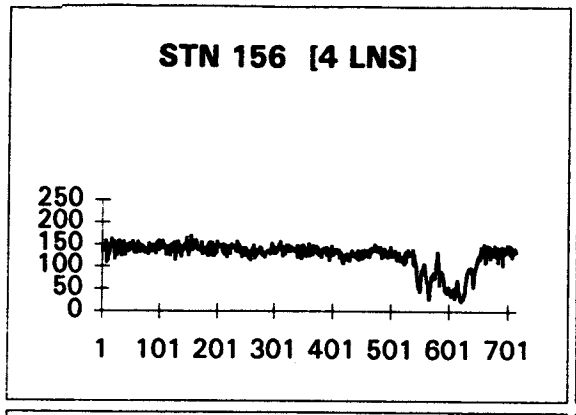
BAD DATA

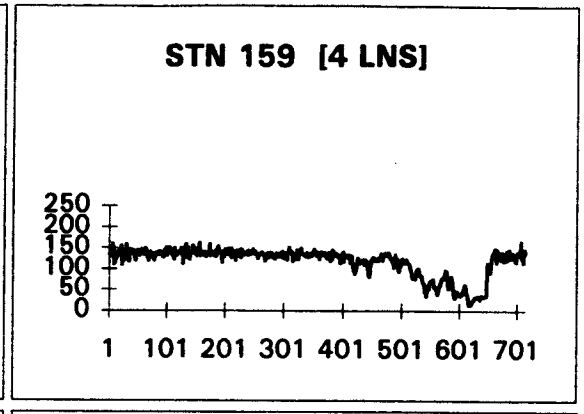


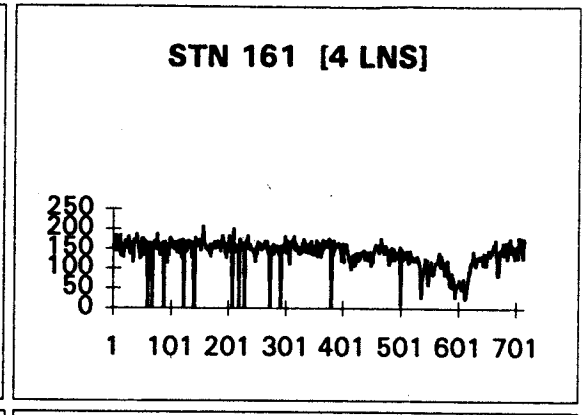


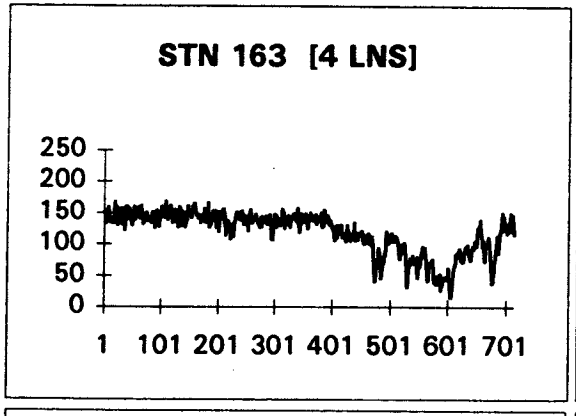
Date of Collection: 12/15/93

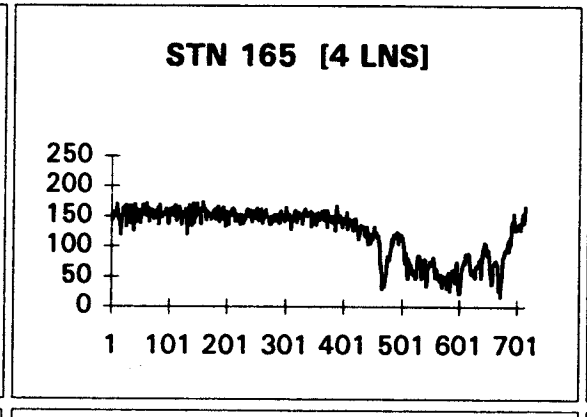
Flow/Occupancy Ratio vs Time Interval

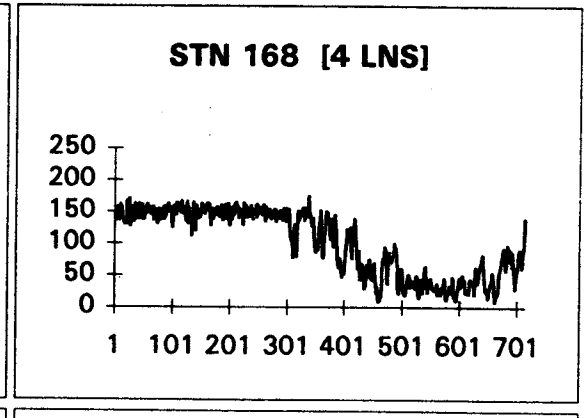


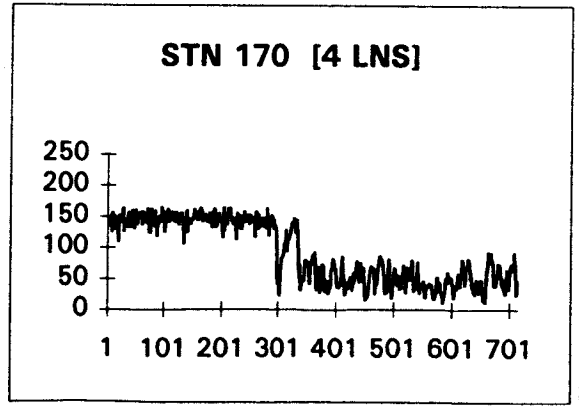


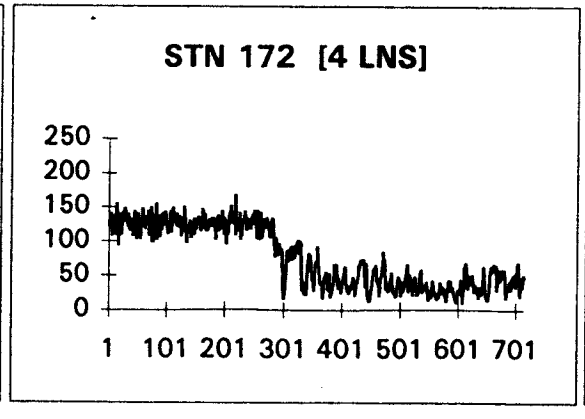


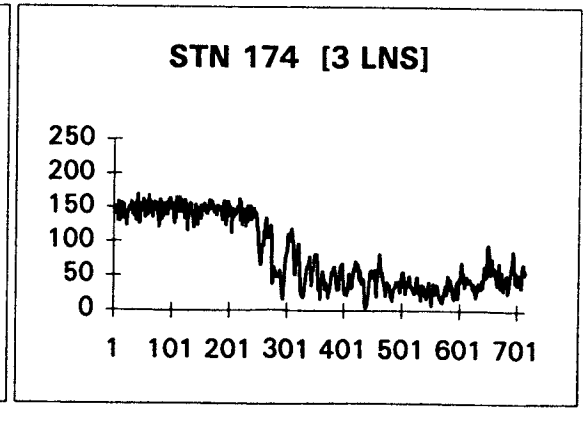






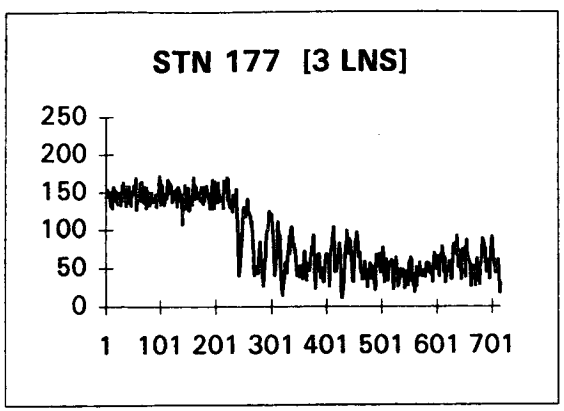


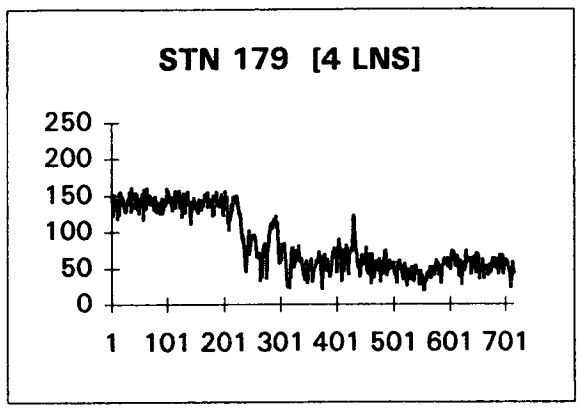


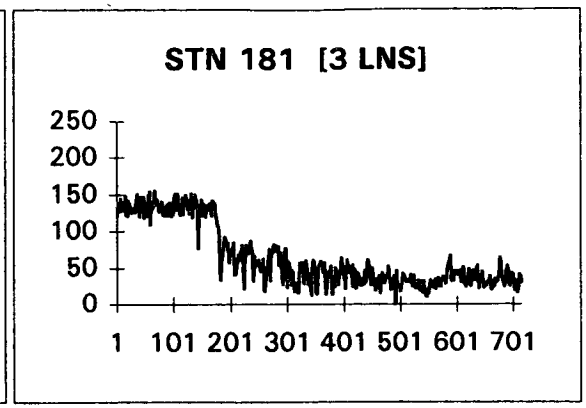


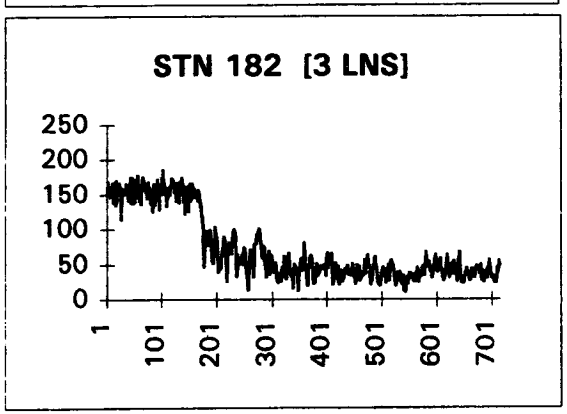
Date of Collection: 12/15/93

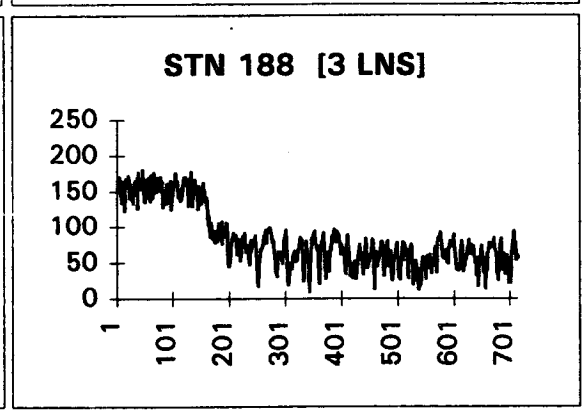
Flow/Occupancy Ratio vs Time Interval

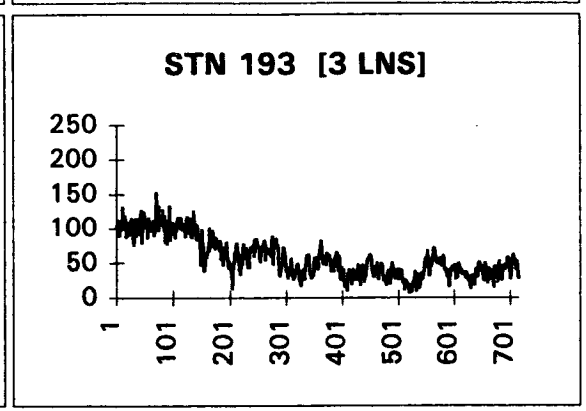






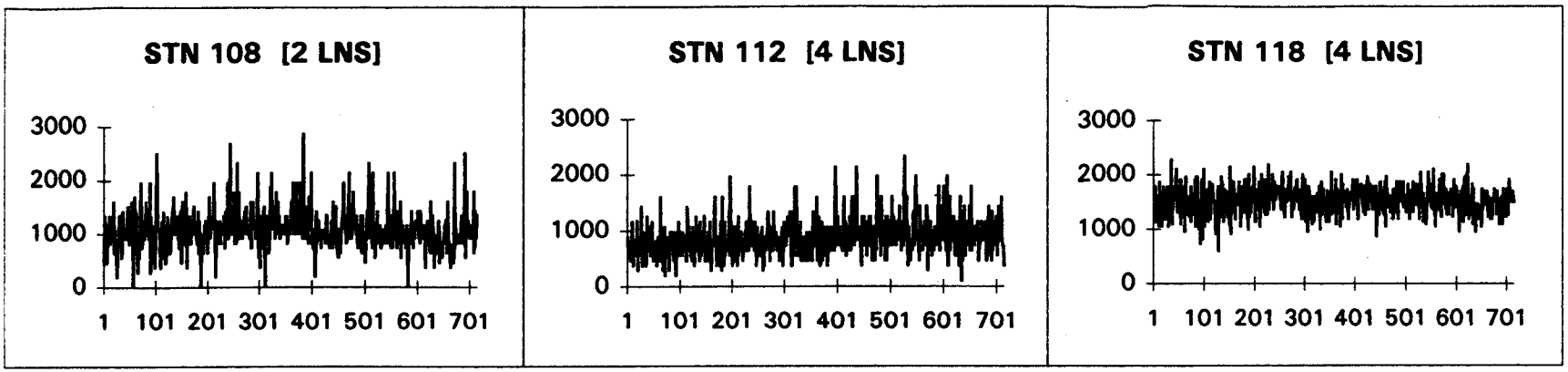


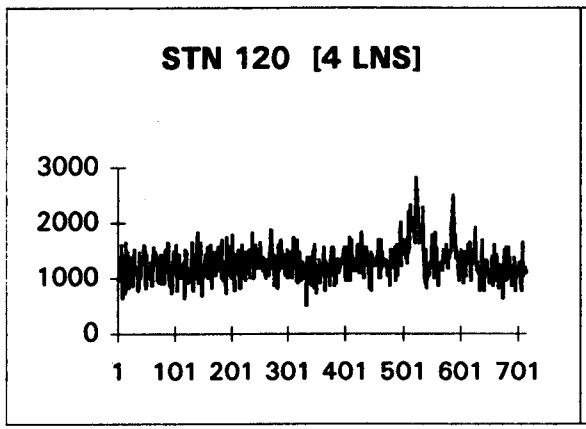


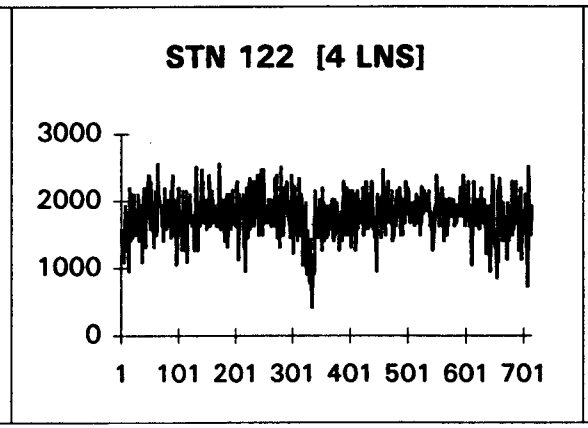


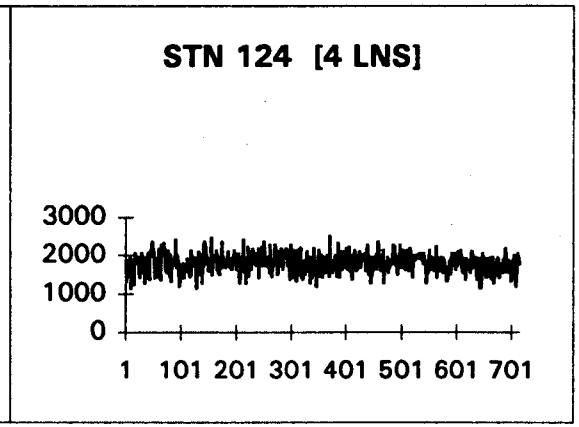
Date of Collection: 12/15/93

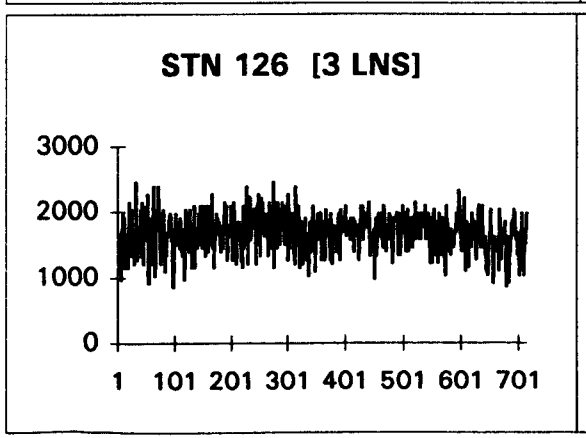
Flow Rate vs Time Interval

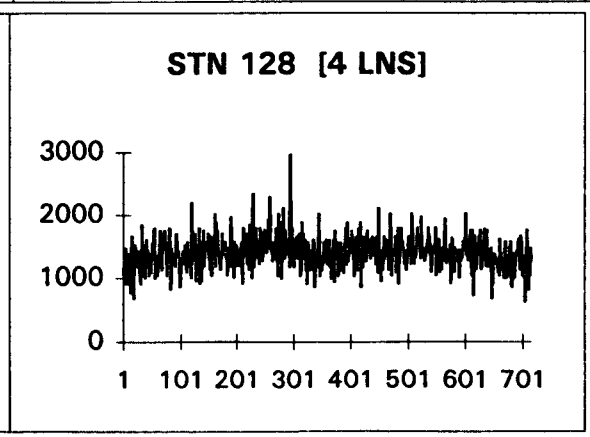










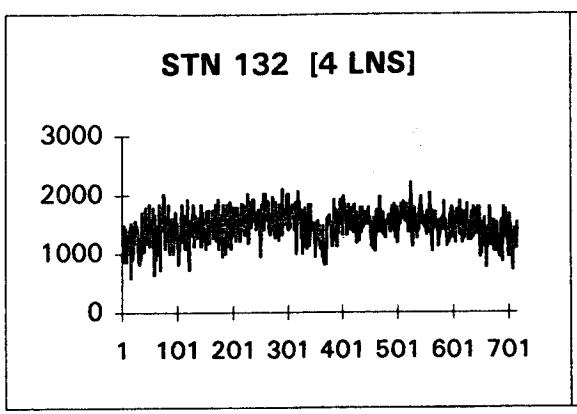


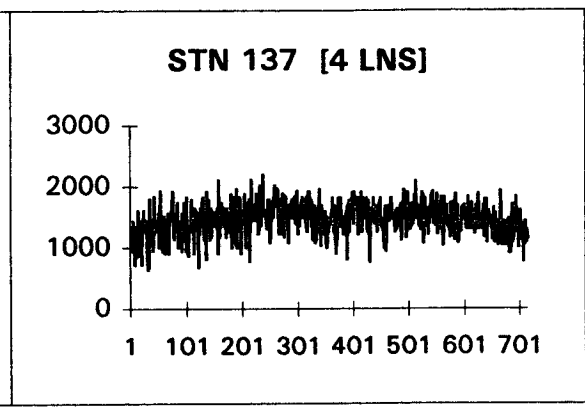
STN 130

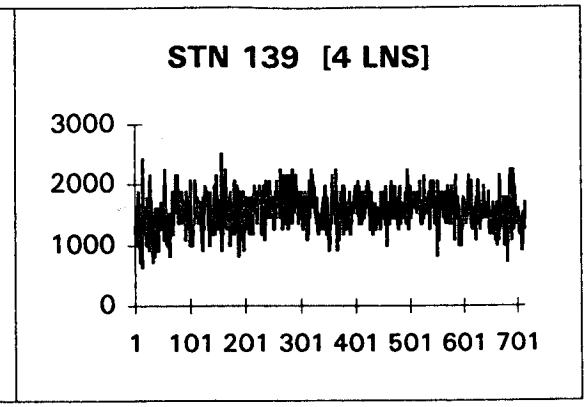
BAD DATA

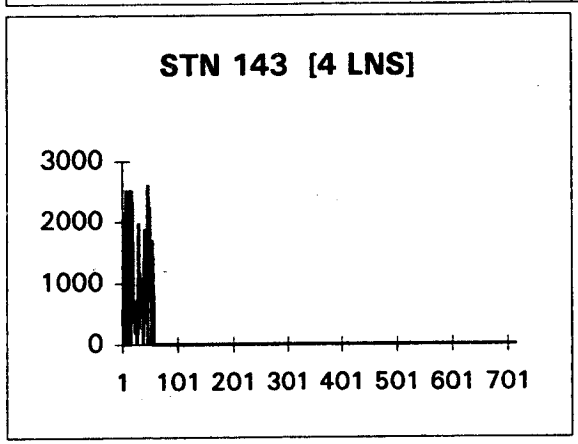
Date of Collection: 12/15/93

Flow Rate vs Time Interval



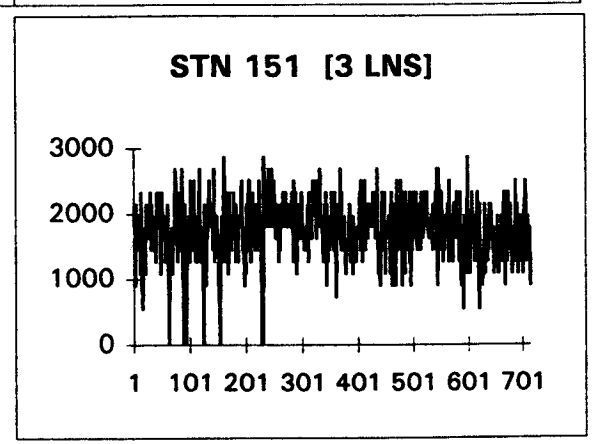


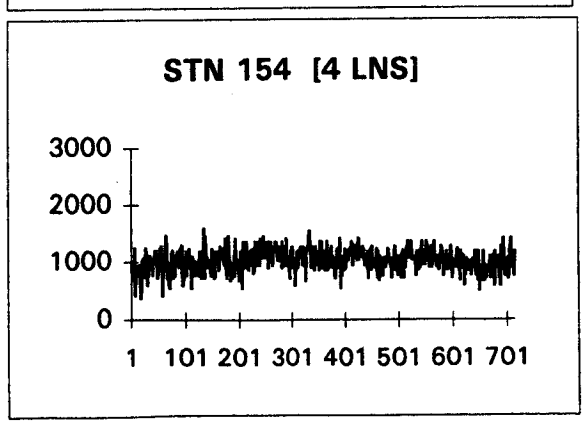




STN 146

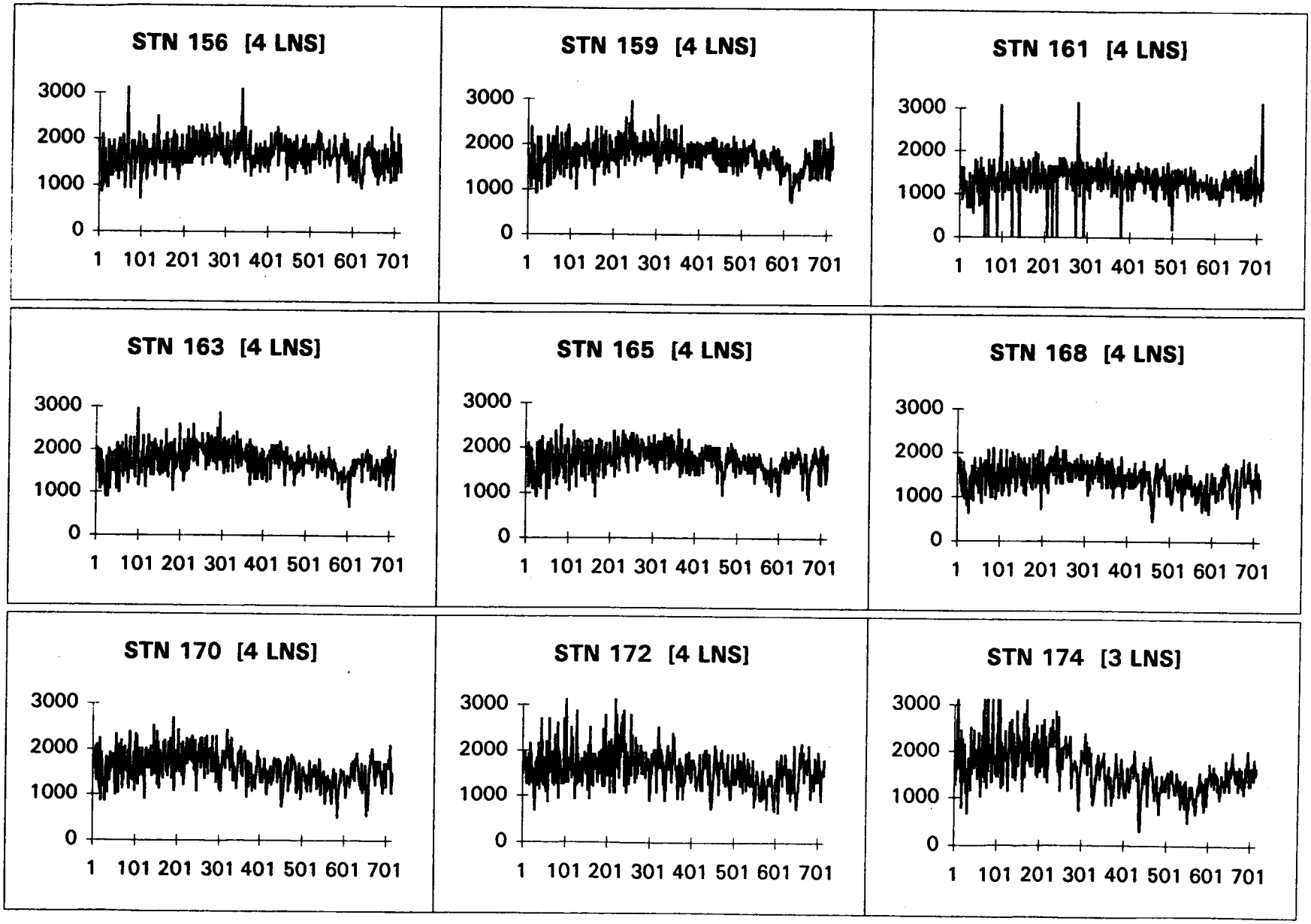
BAD DATA





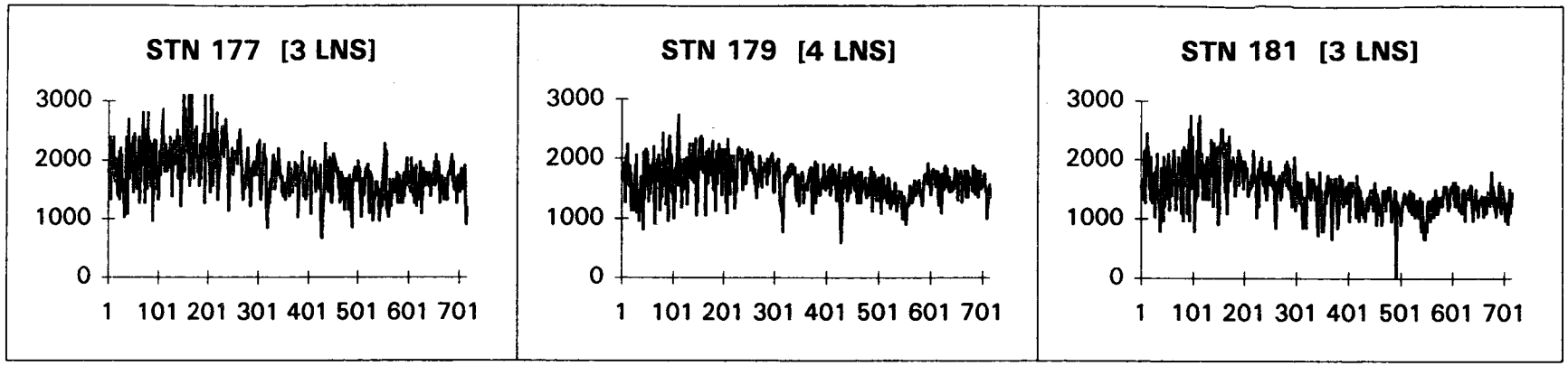
Date of Collection: 12/15/93

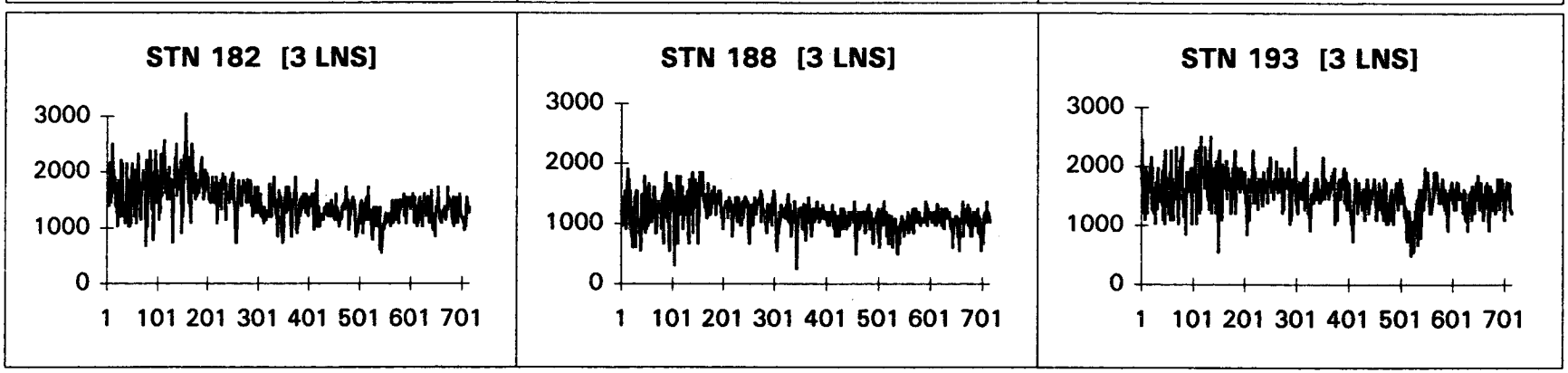
Flow Rate vs Time Interval



Date of Collection: 12/15/93

Flow Rate vs Time Interval



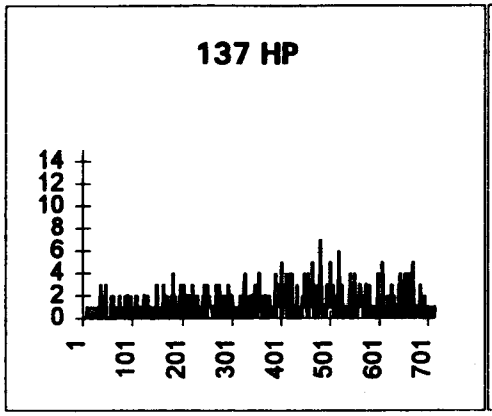


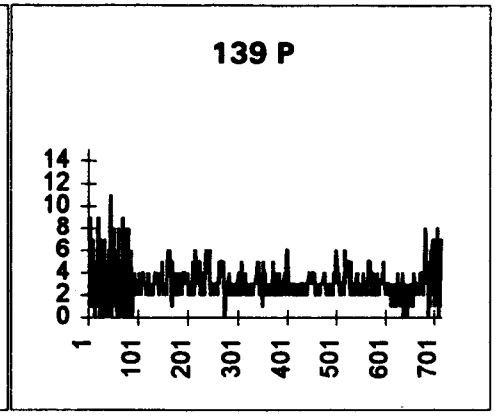
Date of Collection: 12/15/93

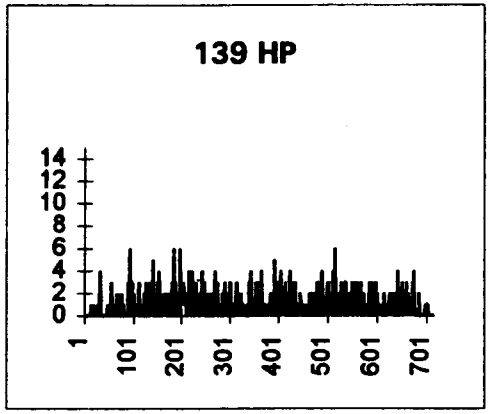
Metered Volume vs Time Interval

137 P

NO DATA

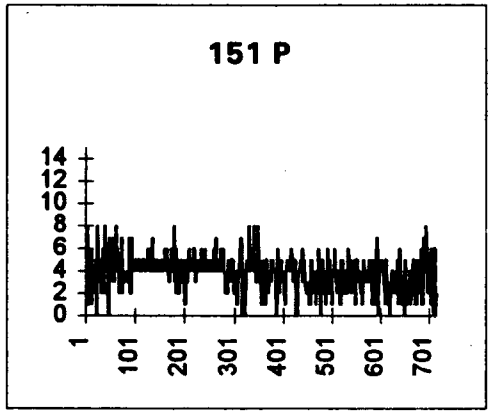






146 D

NO DATA



159 P

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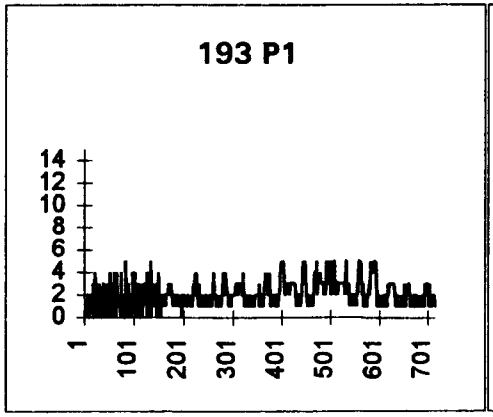
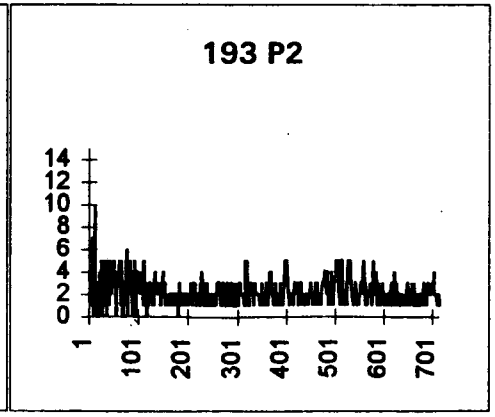
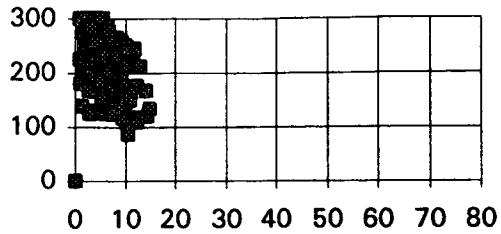


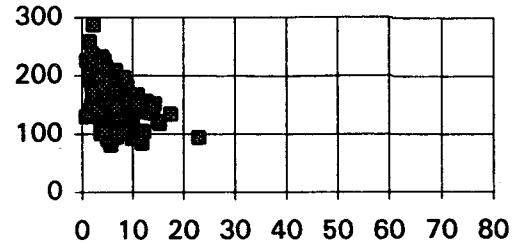


Flow/Occupancy Ratio vs Occupancy

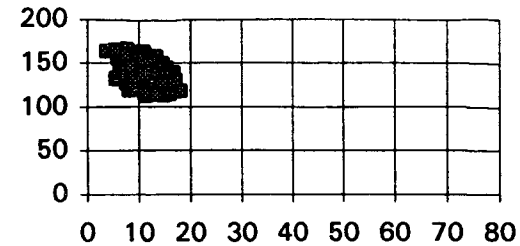
STN 108 [2 LNS]



STN 112 [4 LNS]



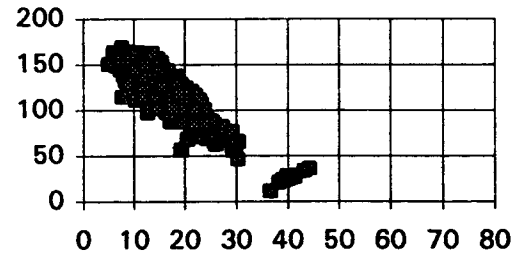
STN 118 [4 LNS]



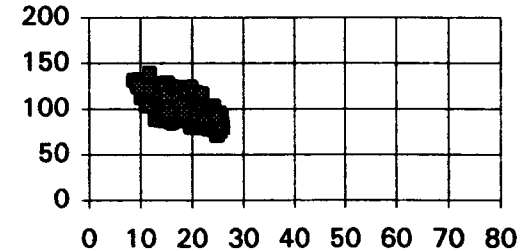
STN 120

BAD DATA

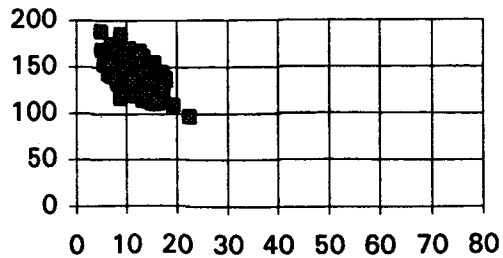
STN 122 [4 LNS]



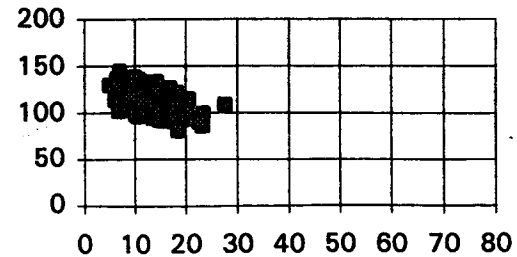
STN 124 [4 LNS]



STN 126 [3 LNS]



STN 128 [4 LNS]

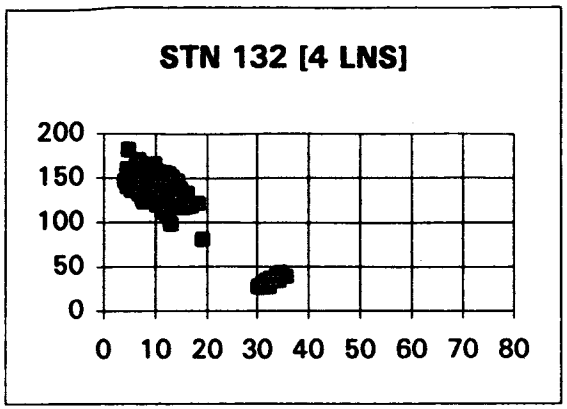


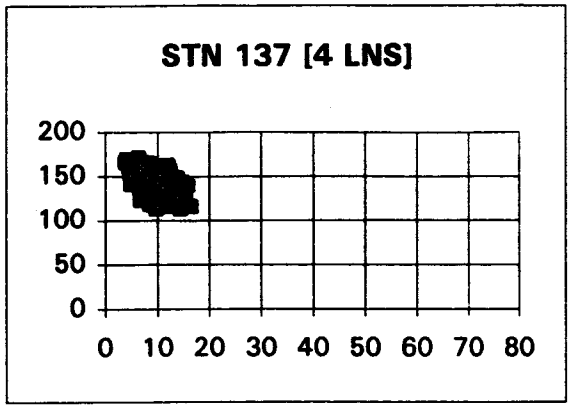
STN 130

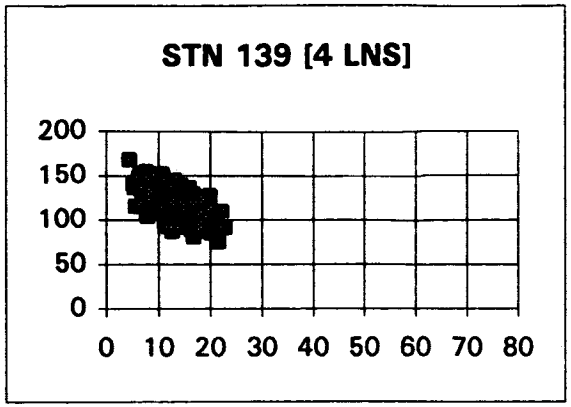
BAD DATA

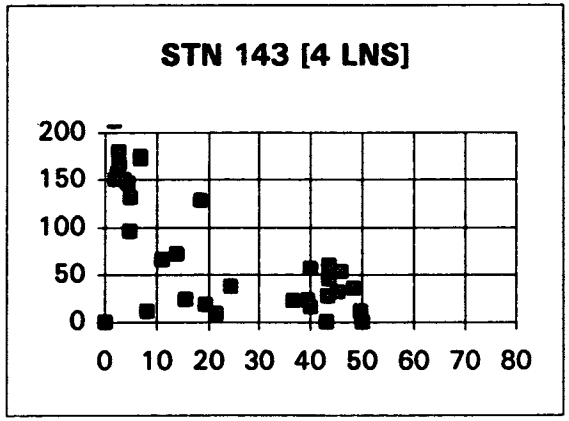
Date of Collection: 12/15/93

Flow/Occupancy Ratio vs Occupancy



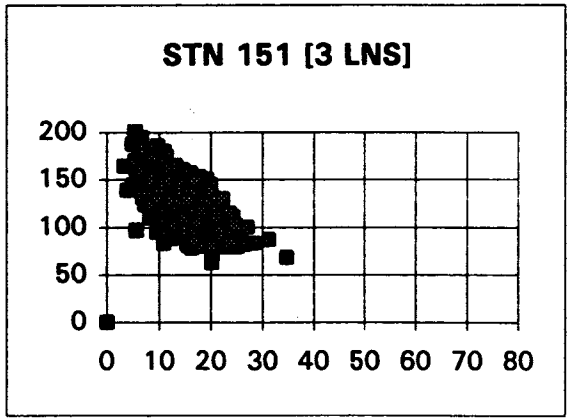


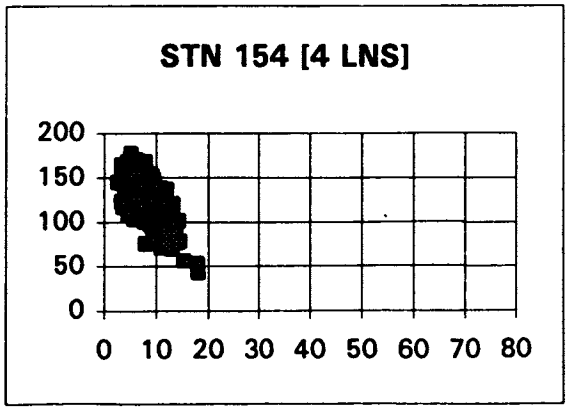




STN 146

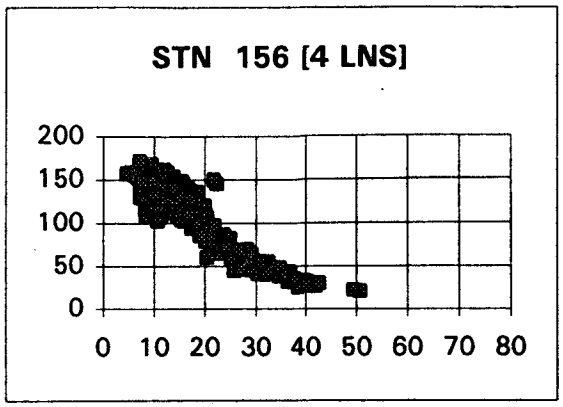
BAD DATA

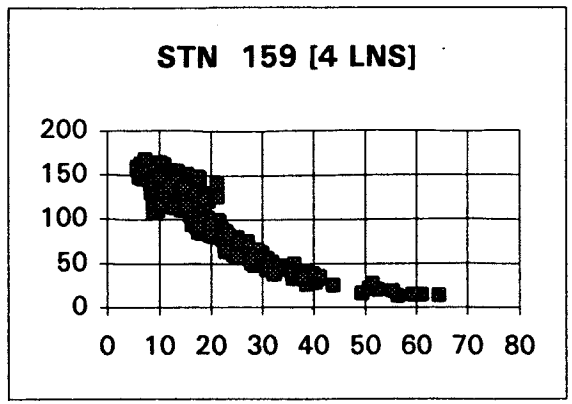


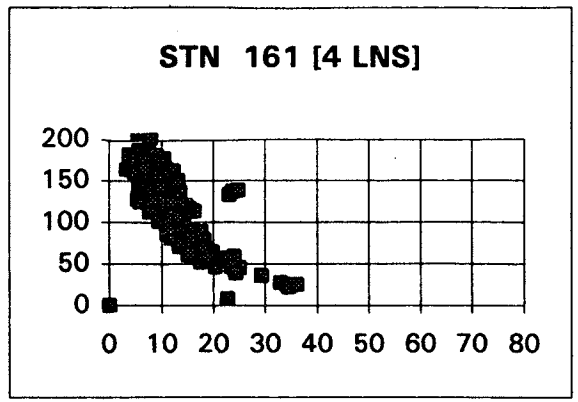


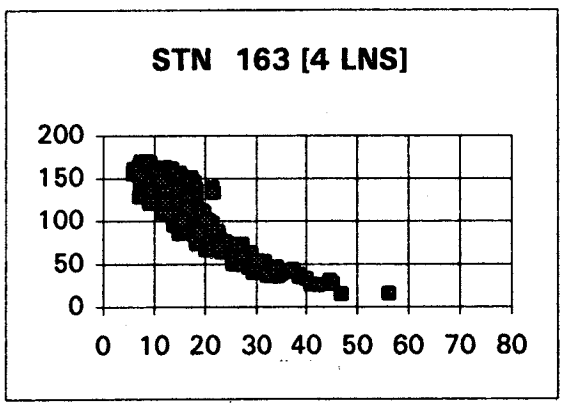
Date of Collection: 12/15/93

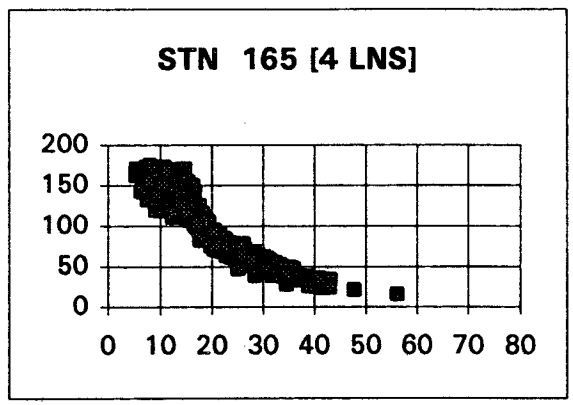
Flow/Occupancy Ratio vs Occupancy

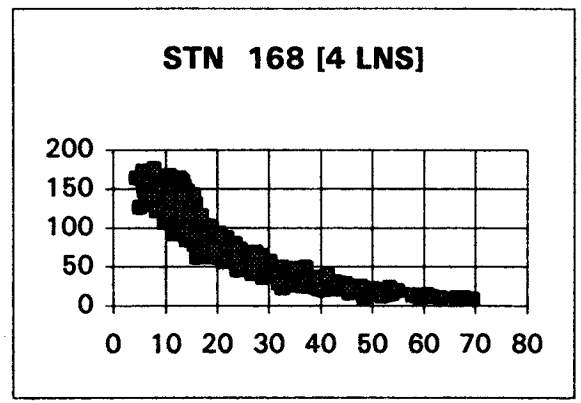


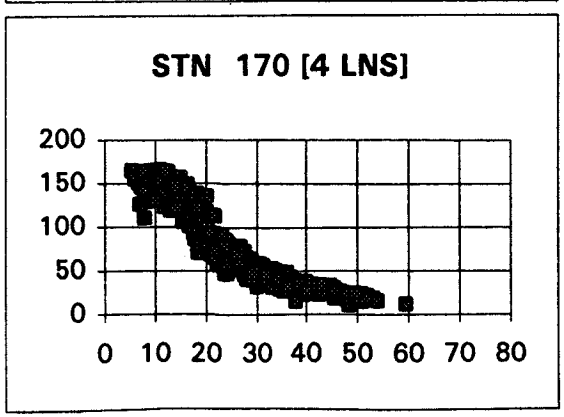


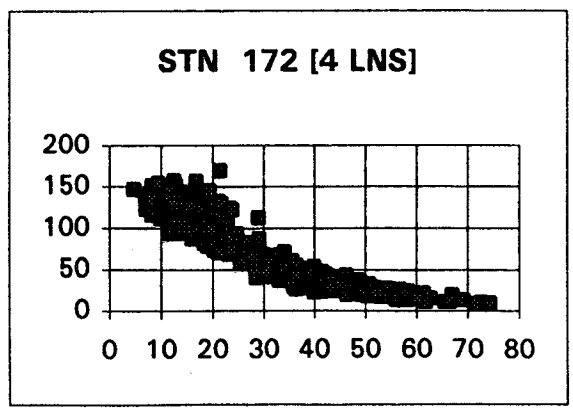


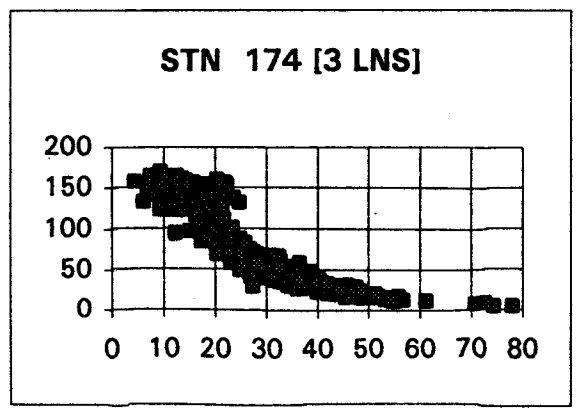






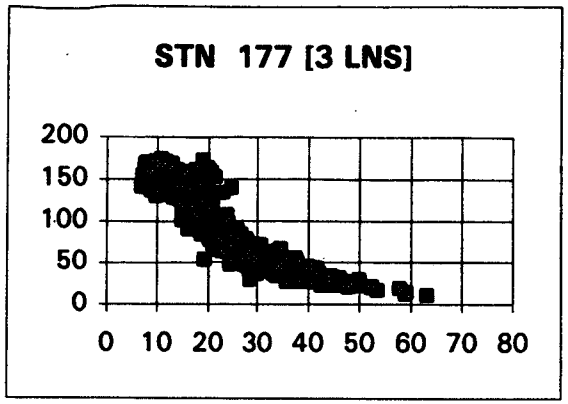


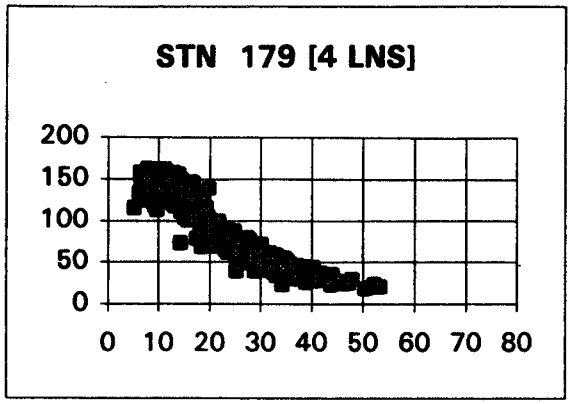


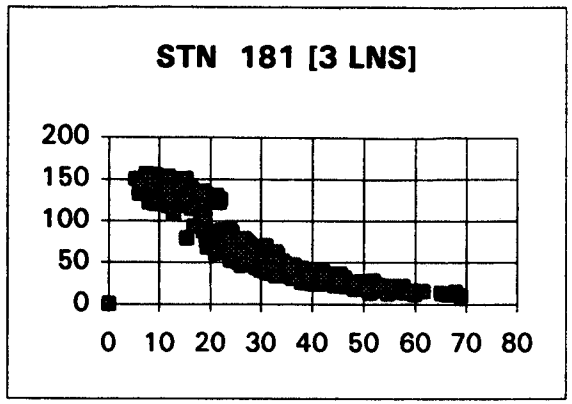


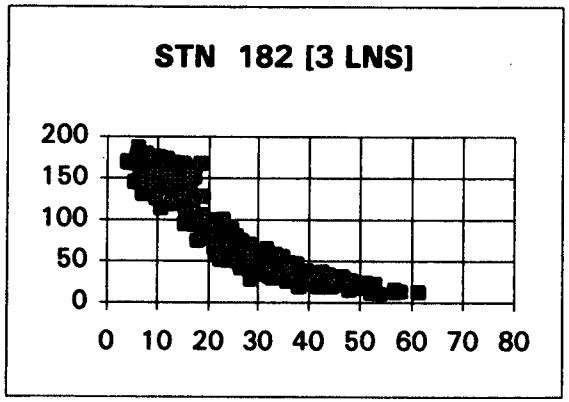
Date of Collection: 12/15/93

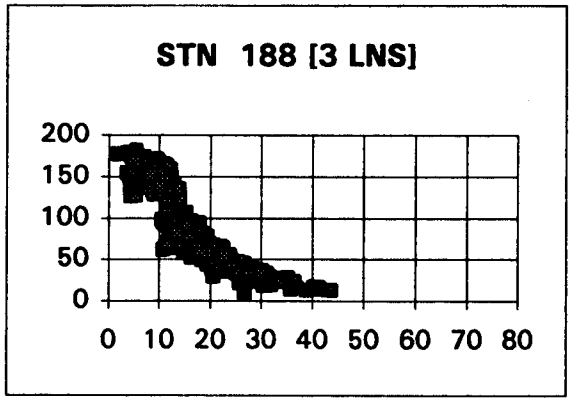
Flow/Occupancy Ratio vs Occupancy

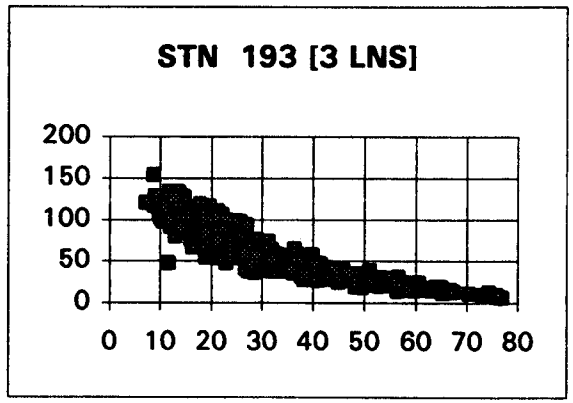












Date of Collection: 12/15/93