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STATISTICAL MODELS OF SEWAGE WASTE GENERATION RATES ABOARD THE --ETC(U)
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STATISTICAL MODELS OF SEWAGE WASTE GENERATION RATES ABOARD THE
USS HAROLD J. ELLISON (DD 864)

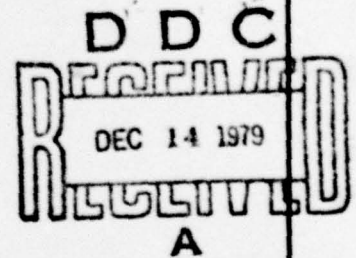
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**STATISTICAL MODELS OF SEWAGE WASTE GENERATION RATES
ABOARD THE USS HAROLD J. ELLISON (DD 864)**

by
**Wolfgang F. Hoffmann
Johann D. Dretchen**

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**COMPUTATION, MATHEMATICS, AND LOGISTICS DEPARTMENT
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December 1979

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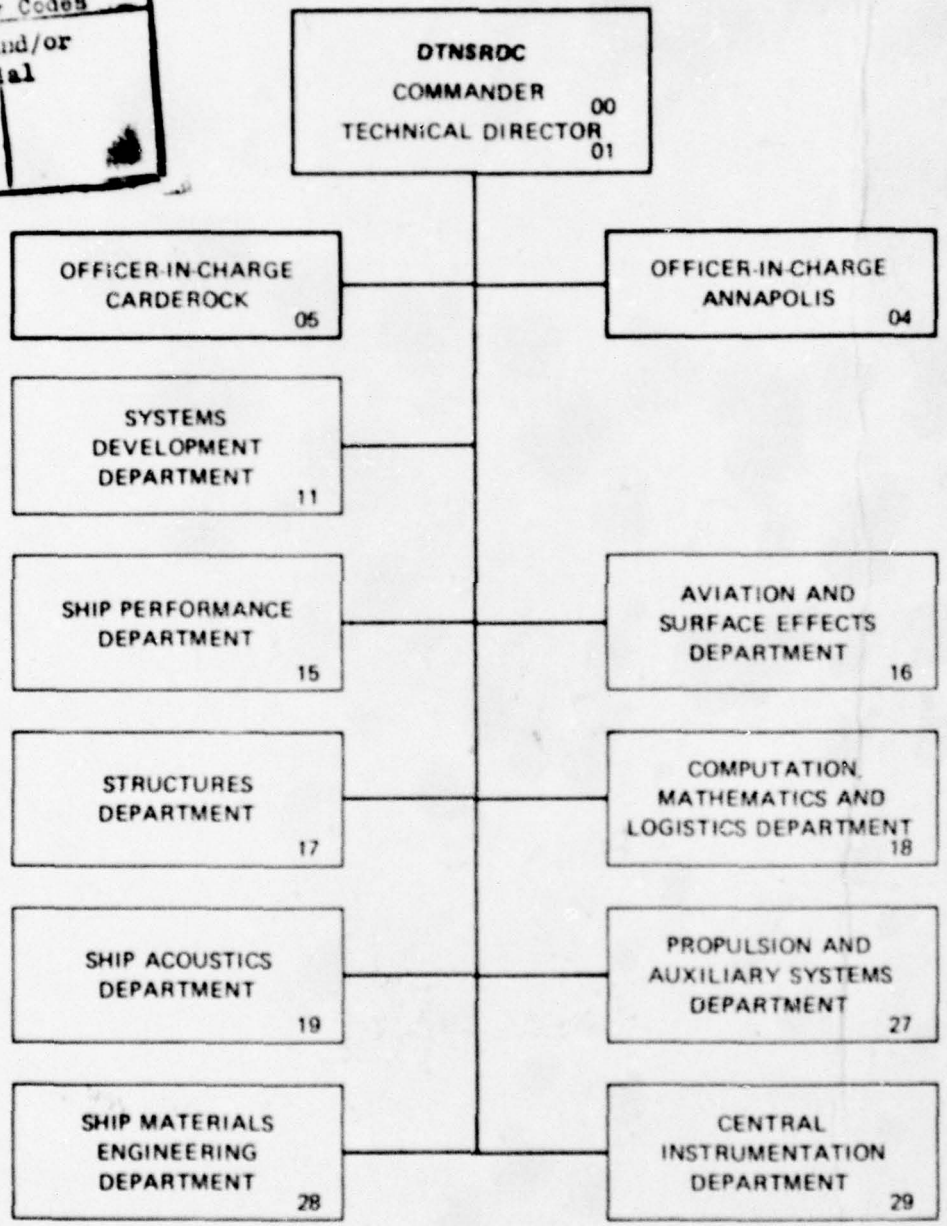
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TABLE OF CONTENTS

	Page
LIST OF FIGURES.....	111
LIST OF TABLES.....	iv
ABSTRACT.....	1
ADMINISTRATIVE INFORMATION.....	1
INTRODUCTION.....	1
BASELINE FLOW DATA DESCRIPTION.....	2
MODEL DEVELOPMENT.....	5
GENERAL MODEL DESCRIPTION.....	5
IDENTIFICATION OF MODEL FORM.....	6
ESTIMATION OF PARAMETERS.....	6
MODEL IDIOSYNCRASY.....	11
DIAGNOSTIC CHECKS ON FIT.....	12
MODEL EXTRAPOLATION TO FLEET.....	21
REFERENCES.....	25
APPENDIX - BASELINE FLOW DATA LISTING.....	27

LIST OF FIGURES

1 - Sample Flow Fluctuations--In Port.....	3
2 - Sample Flow Fluctuations--At Sea.....	4
3 - Autocorrelation and Spectral Density Estimates--In Port.....	9
4 - Autocorrelation and Spectral Density Estimates--At Sea.....	10
5 - Autocorrelation and Spectral Density Estimates of Residuals--In Port.....	13
6 - Autocorrelation and Spectral Density Estimates of Residuals--At Sea.....	14

	Page
7 - Autocorrelation and Spectral Density Estimates of In Port Simulation.....	19
8 - Autocorrelation and Spectral Density Estimates of At Sea Simulation.....	20

LIST OF TABLES

1 - Autocovariance, Autocorrelation and Spectral Density Estimates--In Port.....	7
2 - Autocovariance, Autocorrelation and Spectral Density Estimates--At Sea.....	8
3 - Maximum Likelihood Estimates of Model Parameters.....	11
4 - Autocovariance, Autocorrelation and Spectral Density Estimates of Residuals--In Port.....	15
5 - Autocovariance, Autocorrelation and Spectral Density Estimates of Residuals--At Sea.....	16
6 - Autocovariance, Autocorrelation and Spectral Density Estimates of In Port Simulation.....	17
7 - Autocovariance, Autocorrelation and Spectral Density Estimates of At Sea Simulation.....	18
8 - Per Capita MEAN and VAR Estimates for Model Application.....	23

ABSTRACT

Aft Head sewage waste generation data collected at 15-minute intervals onboard the USS HAROLD J. ELLISON, (DD 864) both in port and at sea, are analyzed by Box-Jenkins time series analysis techniques. Results show that both in-port and at-sea data may be modeled by pure autoregressive Gaussian Processes with dependence order three for in-port data and order one for at-sea data. Maximum likelihood parameter estimates are provided and model fit checks are performed. A method is provided to extrapolate model results to other U.S. Navy ships.

ADMINISTRATIVE INFORMATION

This task was accomplished under Work Unit 1-2864-503 as part of an overall project to characterize the waste streams of U.S. Navy ships as tasked to this Department under the Naval Environmental Protection Support Service (NEPSS) NCBC Project Order 8-0011.

INTRODUCTION

The David W. Taylor Naval Ship Research and Development Center (DTNSRDC) surveyed sewage waste generation aboard the USS HAROLD J. ELLISON as part of an ongoing effort to characterize the non-oily aqueous waste streams discharged to the environment by U.S. Navy ships. Shipboard waste surveys, including this particular effort, are generally sponsored by the Navy Environmental Protection Support Service (NEPSS). In addition to the usual quantity and quality monitoring performed over the period 5 November 1974 to 23 March 1975, specific waste sources were monitored continuously over shorter periods to provide information on flow rate fluctuations at small time increments.

This report describes the methodology used in analyzing the flow rate fluctuation data obtained from continuous monitoring of the Aft Enlisted Head (combined commode and urinal flush wastes) and the resulting random process models deduced from the analysis. Although other major waste sources onboard the ELLISON were also monitored continuously, this report

is specifically limited to the Aft Enlisted Head source to demonstrate methodology and approach.

In the following report, it is assumed that the Aft Enlisted Head flow rate fluctuations can be characterized by a specific form of the family of Autoregressive Integrated Moving Average (ARIMA) models described by Box and Jenkins.^{1*} The basic philosophy and techniques of the Box-Jenkins stochastic model building approach (identification, estimation, checking) are used in this report, supplemented by more precise statistical techniques in the model identification portion of the analysis.

BASELINE FLOW DATA DESCRIPTION

The baseline flow data to which the analysis will be applied were obtained during the period 2-12 December 1974 from the Aft Enlisted Head soil drains. The recording method was an event recorder which provided an indicator mark on a strip chart each time a total of 10 gallons of waste passed through a metering device. Indicator marks were counted in each 15-minute period during the ten-day period. Small gaps (usually less than one hour) occurred at the time of strip chart replacement but, due to their infrequent occurrence and short duration, were assumed to represent zero flow periods. The resulting data provided a continuous flow record for a three-day at-sea period (3-5 December) and a six-day in-port period (6-11 December). Preliminary evaluation of the data indicated that 6, 7, and 8 December had significantly different flow characteristics from the rest of the period because of the inclusion of a debarkation day (6 December) and a weekend. These data were subsequently eliminated from consideration in the analysis, leaving three full days of waste flow data for normal in-port and at-sea operations.

The data presented in the Appendix are in units of tens of gallons per 15 minutes. Figures 1 and 2 show in-port and at-sea flow fluctuations, respectively, for one 24-hour period.

*A complete listing of references is given on page 25.

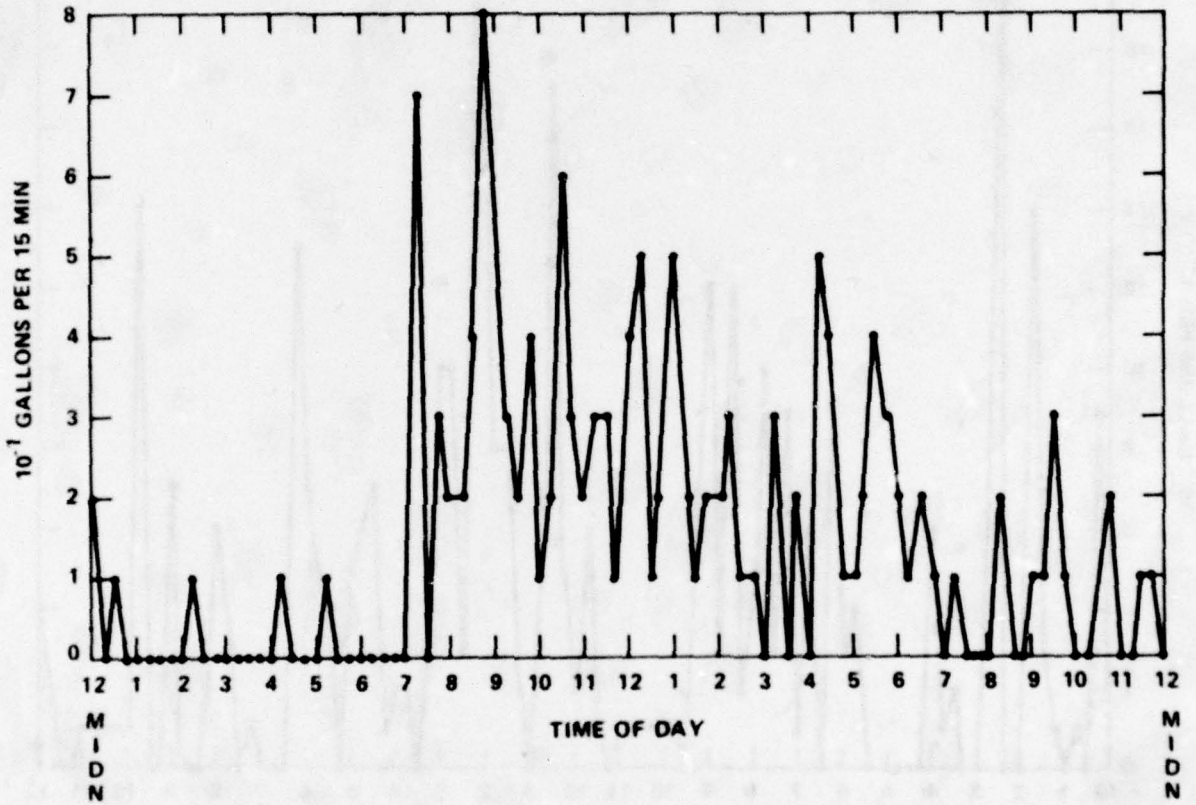


Figure 1 - Sample Flow Fluctuations
IN PORT

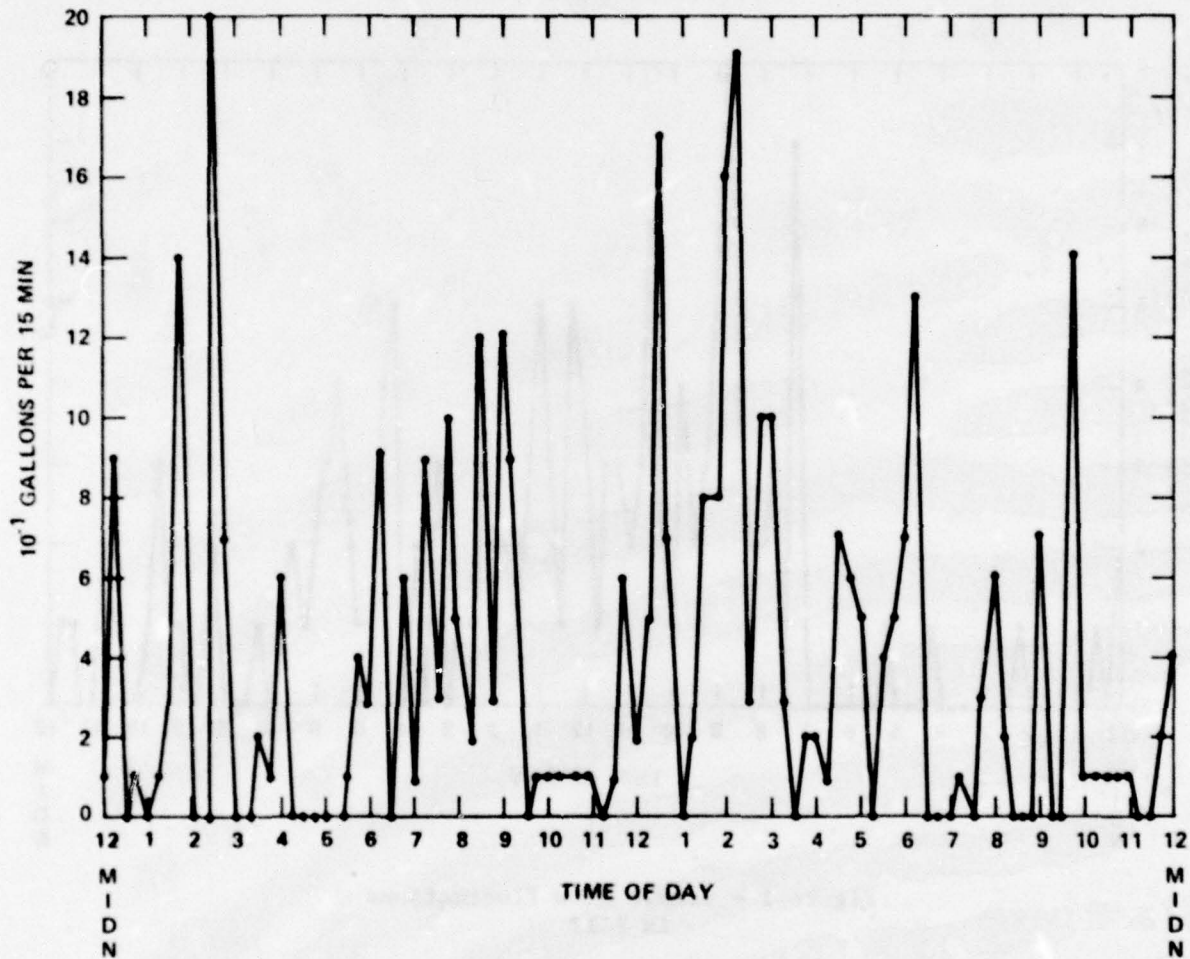


Figure 2 - Sample Flow Fluctuations
AT SEA

MODEL DEVELOPMENT

GENERAL MODEL DESCRIPTION

The family of ARIMA random process models described by Box and Jenkins¹ provides a mathematical representation of a wide variety of characteristics of random fluctuations observed in time series. Stationary (constant mean), linear non-stationary (random mean level changes), and seasonal (cyclic-pattern repetition) are easily represented in this family of models.

Since the subsequent models identified are of the stationary form, we will briefly summarize the characteristics of this type of model. If z_t , $t=1,2,\dots$ represents the random values associated with a stationary time series, then the model form is

$$z_t = c + \phi_1 z_{t-1} + \phi_2 z_{t-2} + \dots + \phi_p z_{t-p} \\ + a_t - \theta_1 a_{t-1} - \theta_2 a_{t-2} - \dots - \theta_q a_{t-q}$$

where c is a constant

ϕ_i, θ_j are constant coefficients

a_t is a Normal (Gaussian) random variable with zero mean and variance σ_a^2

p, q are the dependence orders associated with z_t and a_t , respectively

As the model indicates, the current value of z_t is dependent on proportional values of p previous z 's and q previous a 's. The dependency relations are not intended to display causal relationships but merely reflect the fluctuation pattern as z evolves in time. No physical interpretation can therefore be assigned unless additional information is available.

The model is developed by first identifying the values p and q which define the order of dependence, estimating the parameter values ϕ_i , $i=1,2,\dots,p$, θ_j , $j=1,2,\dots,q$, and then checking the fit by analysis of residual values. This sequence of procedures revolves around the autocorrelation estimates and defines the basic Box-Jenkins model building philosophy. The analysis procedures, the results of which are described

below, have been applied to the "at-sea" and "in-port" portions of the data of the Appendix separately.

IDENTIFICATION OF MODEL FORM

The autocovariance, autocorrelation, and spectral density estimates for the first twenty lags are given in Tables 1 and 2 for in-port and at-sea data, respectively. Figures 3 and 4 provide the corresponding information graphically. The structure of the flow variation shown in Figures 1 and 2 and the pattern of the autocorrelation and spectral density estimates indicate that both the in-port and at-sea fluctuations are stationary about a constant mean and are most likely pure autoregressive (AR) processes (i.e., $p > 0$, $q=0$ in the general model described in the preceding section of this report).

To verify these initial indications and obtain optimal values for p , both sets of data were passed through IMSL² subroutine FTCOMP. FTCOMP did indeed verify the initial estimates and provided optimal values of $p=1$ for the at-sea fluctuation and $p=3$ for the in-port version, with $q=0$ for both sets. In addition, FTCOMP confirmed the stationarity assumptions previously made. These results imply that the data are best fitted by pure autoregressive (AR) models of the form

in port

$$z_t = c + \phi_1 z_{t-1} + \phi_2 z_{t-2} + \phi_3 z_{t-3} + a_t$$

at sea

$$z_t = c + \phi_1 z_{t-1} + a_t$$

These models may be designated as AR(3) and AR(1), respectively.

ESTIMATION OF PARAMETERS

In addition to optimal selection of the model form, FTCOMP also provides Maximum Likelihood Estimates (MLE's) of the parameters of the selected model. Table 3 shows the results of these computations for both in-port and at-sea models and also shows the mean and variance estimates of each time series.

TABLE 1 - AUTOCOVARANCE, AUTOCORRELATION AND SPECTRAL DENSITY ESTIMATES
IN PORT

LAG	SAMPLE UNWEIGHTED	SAMPLE AUTOCOVARANCE WEIGHTED	SAMPLE UNWEIGHTED	AUTOCORRELATION WEIGHTED	SPECTRUM	SPECTRAL DENSITY	LOGARITHMIC SPECTRUM	PERIOD
0	2.38407	2.38407	1.0000	1.0000	1.77102	.7679	.248223	INFINITE
1	.868716	.456345	.3644	.3592	1.46207	.5981	-.146769	40.0000
2	.645028	.510197	.2706	.2559	.71950	.3396	-.131055	20.0000
3	.652364	.581029	.2753	.2837	.37481	.1616	-.471749	13.3333
4	.741646	.543283	.3111	.2514	.219519	.0921	-.658528	10.0000
5	.748054	.535279	.3129	.2249	.248983	.1027	-.611044	8.0000
6	.660714	.413644	.2708	.1734	.122372	.1751	-.492048	6.6667
7	.575355	.300879	.2413	.1260	.158822	.1505	-.445121	5.7143
8	.402644	.173721	.1689	.0716	.333453	.1690	-.476445	5.0000
9	.264477	.845161-01	.1119	.0771	.238749	.1253	-.524694	4.4444
10	.342027	.457204E-01	.1578	.0340	.276534	.1163	-.554967	4.0000
11	.308982	.563043E-01	.1296	.1236	.276645	.1182	-.541165	3.6364
12	.233126	.238632E-01	.0779	.0125	.263516	.1195	-.579193	3.3333
13	.327456	.211222E-01	.1376	.0118	.226431	.0940	-.545065	3.0769
14	.174077	.953172E-02	.5719	.0340	.219446	.0479	-.478846	2.8571
15	.603056-01	.187595E-02	.2252	.0268	.233772	.0333	-.650194	2.6667
16	.159281	.254814E-02	.0668	.0011	.225654	.0467	-.646549	2.5000
17	.205574	.135147E-02	.0441	.0306	.215174	.0312	-.667304	2.3529
18	.995251E-01	.139050E-03	.0417	.1501	.212403	.0491	-.572845	2.2222
19	.227818E-01	.569546E-05	.0094	.0800	.212843	.0491	-.672962	2.1053
20	.402101E-01		.0254		.211127	.0496	-.675457	2.0000

PARZEN WEIGHTING FUNCTION

OBSERVATIONS 244 MISSING 3 N OF LAGS 20 TIME UNIT MINUTE
 VARIANCE RATIO .174516E-01 DEGREES OF FREEDOM 51 STANDARDIZED BANDWIDTH 1.85430 VARIANCE 2.38407

TABLE 2 - AUTOCOVARANCE, AUTOCORRELATION AND SPECTRAL DENSITY ESTIMATES
AT SEA

LAG	SAMPLE UNWEIGHTED	SAMPLE AUTOCOVARANCE WEIGHTED	SAMPLE UNWEIGHTED	AUTOCORRELATION WEIGHTED	SPECTRUM	SPECTRAL DENSITY	LOGARITHMIC SPECTRUM	PERIOD
0	23.7274	23.7274	1.0000	1.0000	7.92662	.3361	.490077	INFINITE
1	5.97877	5.88569	.2616	.2681	7.43970	.3135	.871555	60.0000
2	1.86370	1.74133	.0776	.0734	6.35655	.2679	.813222	28.0000
3	2.32683	2.34080	.0981	.0888	5.33244	.2204	.726960	13.3333
4	2.27124	1.81516	.0847	.0773	4.56345	.1923	.659293	19.0000
5	3.12904	3.24950	.0132	.0095	4.03125	.1599	.605448	8.0000
6	7.19144	6.87310	.0103	.0189	3.91671	.1450	.592866	6.6667
7	1.86831	1.64236	.0778	.0806	3.88187	.1436	.590035	5.7143
8	-1.07724	-1.854630	-.0452	-.0192	3.58291	.1493	.569360	5.0000
9	5.82122	5.93119	.0245	.0381	3.31264	.1496	.526154	4.4444
10	-1.84864	-2.11712	-.0347	-.0389	3.58800	.1495	.549984	4.0000
11	2.52687	1.60364	.1865	.0194	3.98004	.1665	.591519	3.6364
12	-1.76166	-1.374978-01	-.0321	-.0341	3.71875	.1564	.569462	3.3333
13	2.07198	1.77546E-01	.0587	.0507	3.19524	.1109	.492896	3.0769
14	2.32984	1.95814E-01	.0398	.0205	2.61484	.1102	.417452	2.8571
15	-1.33167	-1.81750E-01	-.0582	-.0018	2.12104	.0906	.326548	2.6667
16	-1.46345	-1.41540E-02	-.0195	-.0003	1.81046	.0445	.281229	2.5000
17	1.66112	1.69275E-02	.0415	.0003	2.42814	.0373	.385310	2.3529
18	1.74487	1.49946E-02	.0735	.0001	2.78299	.0173	.444512	2.2222
19	-1.11524E-01	-1.17876E-04	-.0032	-.0000	2.20654	.0480	.363716	2.1053
20	1.10574	0	.0042	0	1.70711	.0710	.232263	2.0000

OBSERVATIONS 244 MISSING 0 H OF LAGS 20 TIME UNIT MINUTE

VARIANCE RATIO .74514E-01 DEGREES OF FREEDOM 53 STANDARDIZED BANDWIDTH 1.85433 VARIANCE 23.7274

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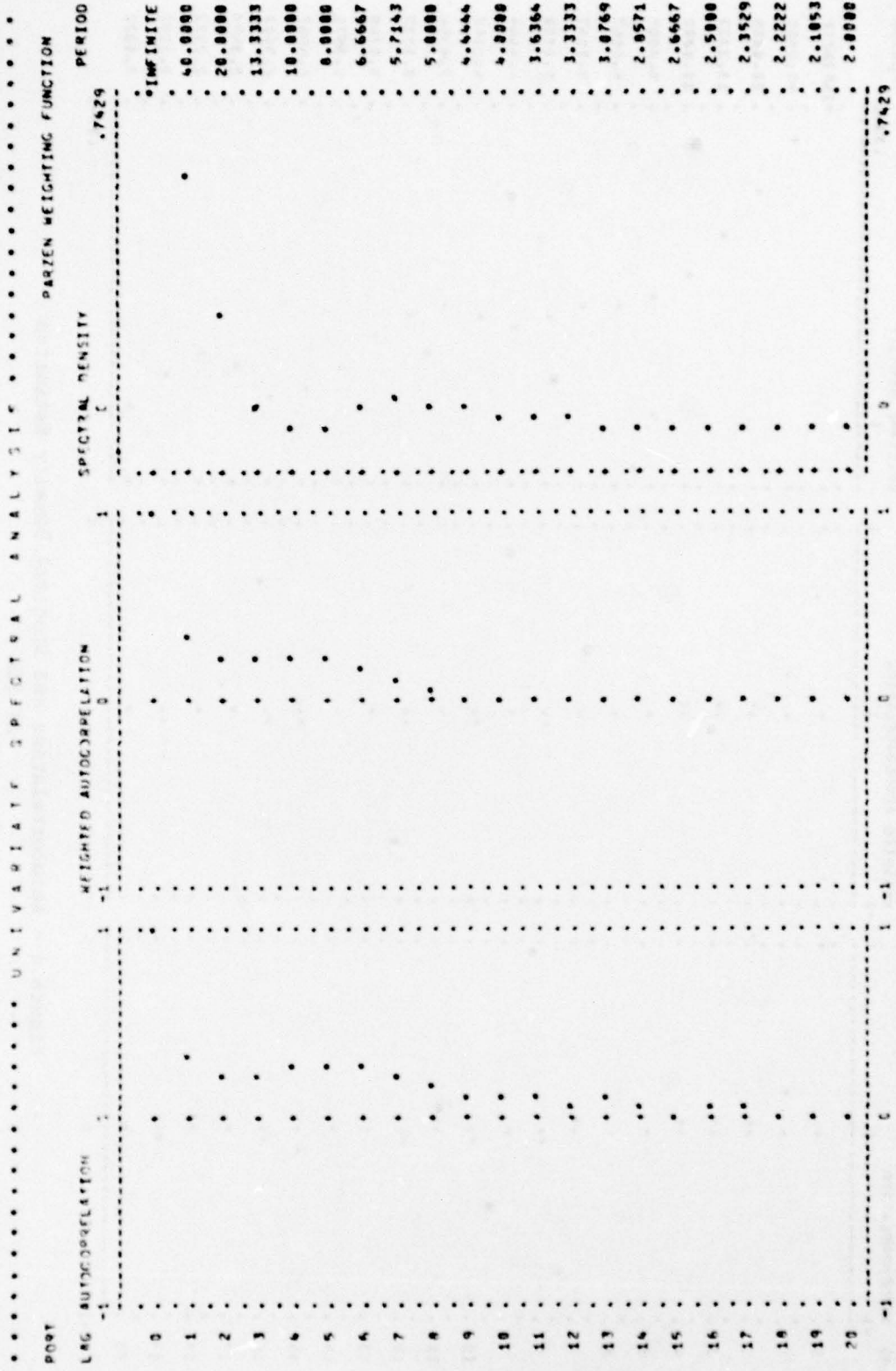


Figure 3 - Autocorrelation and Spectral Density Estimates
IN PORT

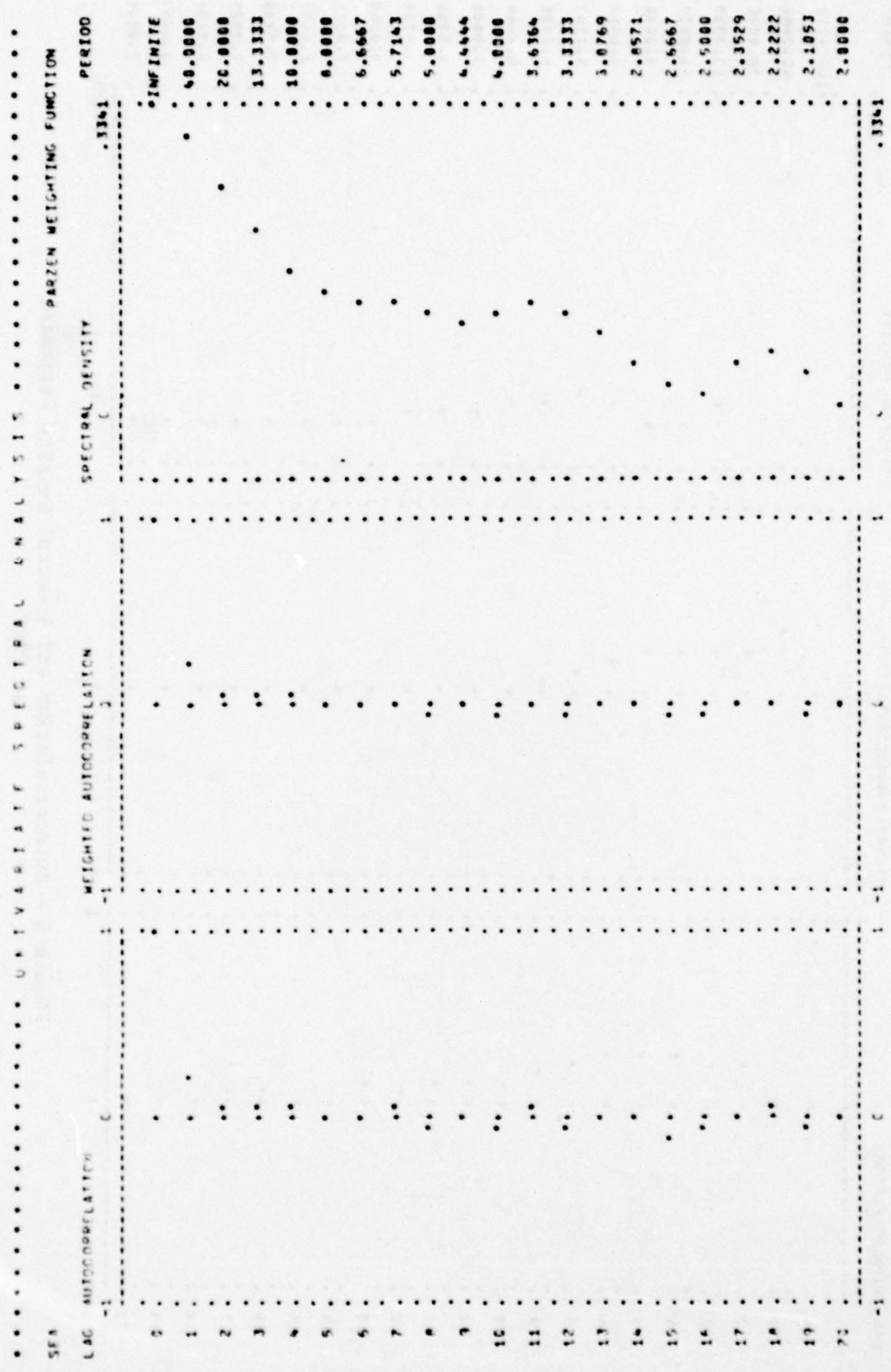


Figure 4 - Autocorrelation and Spectral Density Estimates
AT SEA

TABLE 3 - MAXIMUM LIKELIHOOD ESTIMATES OF MODEL PARAMETERS

	Mean*	Var.**	C*	ϕ_1	σ_a^2
At Sea	3.54	23.72	2.649	$\phi_1 = 0.252$	22.21
In Port	1.32	2.33	0.596	$\phi_1 = 0.278$ $\phi_2 = 0.109$ $\phi_3 = 0.161$	1.95
*In units of 10^{-1} gallons. **In units of $(10^{-1}$ gallons) 2 .					

MODEL IDIOSYNCRASY

ARIMA modeling requires the assumption of a Gaussian distribution for the white noise term a_t and, from theoretical considerations, the multivariate Gaussian distribution of the z 's. As a consequence, under certain conditions on the mean and variance of the distribution, large negative values have large probability of occurrence. This situation exists for both models (in port and at sea) and is incompatible with the physical reality of non-negative flow rates. To compensate for this idiosyncrasy in simulation applications, the following function should be used with the models:

$$w_t = \begin{cases} z_t & \text{if } z_t \geq 0 \\ 0 & \text{otherwise} \end{cases}$$

In probabilistic analyses, the usual Gaussian density integrals should be adjusted by multiplying the results by $1/(1-\text{Prob}[Z_t < 0])$ where

$$\text{Prob}[Z_t < 0] \approx \begin{cases} 0.19 & \text{in port} \\ 0.23 & \text{at sea} \end{cases}$$

DIAGNOSTIC CHECKS ON FIT

Two types of diagnostic checks were performed to determine how well the model fits the data. The first type checks the autocorrelation of residuals for significant residual dependencies and the second checks the spectral density for suspicious periodicities.

Figures 5 and 6 are graphic displays of autocorrelation and spectral density estimates of the residuals shown in Tables 4 and 5. Under the assumption that the residuals are white Gaussian noise with variance σ_a^2 , then the autocorrelation estimates, r_k , of the residuals at lag k should not exceed $\pm 2\sigma(r_k) \approx \pm 2/\sqrt{n}$ (n is the number of sample points) for $k > 0$. Since $n = 288$ for both in port and at sea, $\pm 2\sigma(r_k) \approx \pm 0.118$. It can be seen in Tables 4 and 5 that none of the autocorrelations of the residuals exceed these bounds, except, of course, at lag 0. A more formal check can be performed by computing the statistic

$$Q = n \sum_{k=1}^K r_k^2$$

which is Chi-Square distributed with $(K-p)$ degrees of freedom (d.f.), where K is the number of lags for which the autocorrelation estimates have been computed. For the 20 lags shown in Tables 4 and 5

$$Q \text{ (in port)} = 0.031 \text{ with } (20-3) = 17 \text{ d.f.}$$

$$Q \text{ (at sea)} = 0.012 \text{ with } (20-1) = 19 \text{ d.f.}$$

both of which pass the 0.25 tabulated Chi-Square values by substantial margins. On the basis of these diagnostic tests, both models provide excellent fit to the data.

In the second type of check, the spectral estimates of the residuals, the spectral densities displayed in Figures 5 and 6 indicate some possibility of additional periodic components. However, these periodic components are thought to be the result of the truncation effects described in the previous section. To substantiate this assumption, simulation results for each truncated model, each simulation of length 288, were passed through the spectral analysis and are displayed in Tables 6 and 7 and Figures 7 and 8. These spectral estimates compare favorably in Tables 1 and 2 and Figures 3 and 4 of the original data. Consequently, it may be

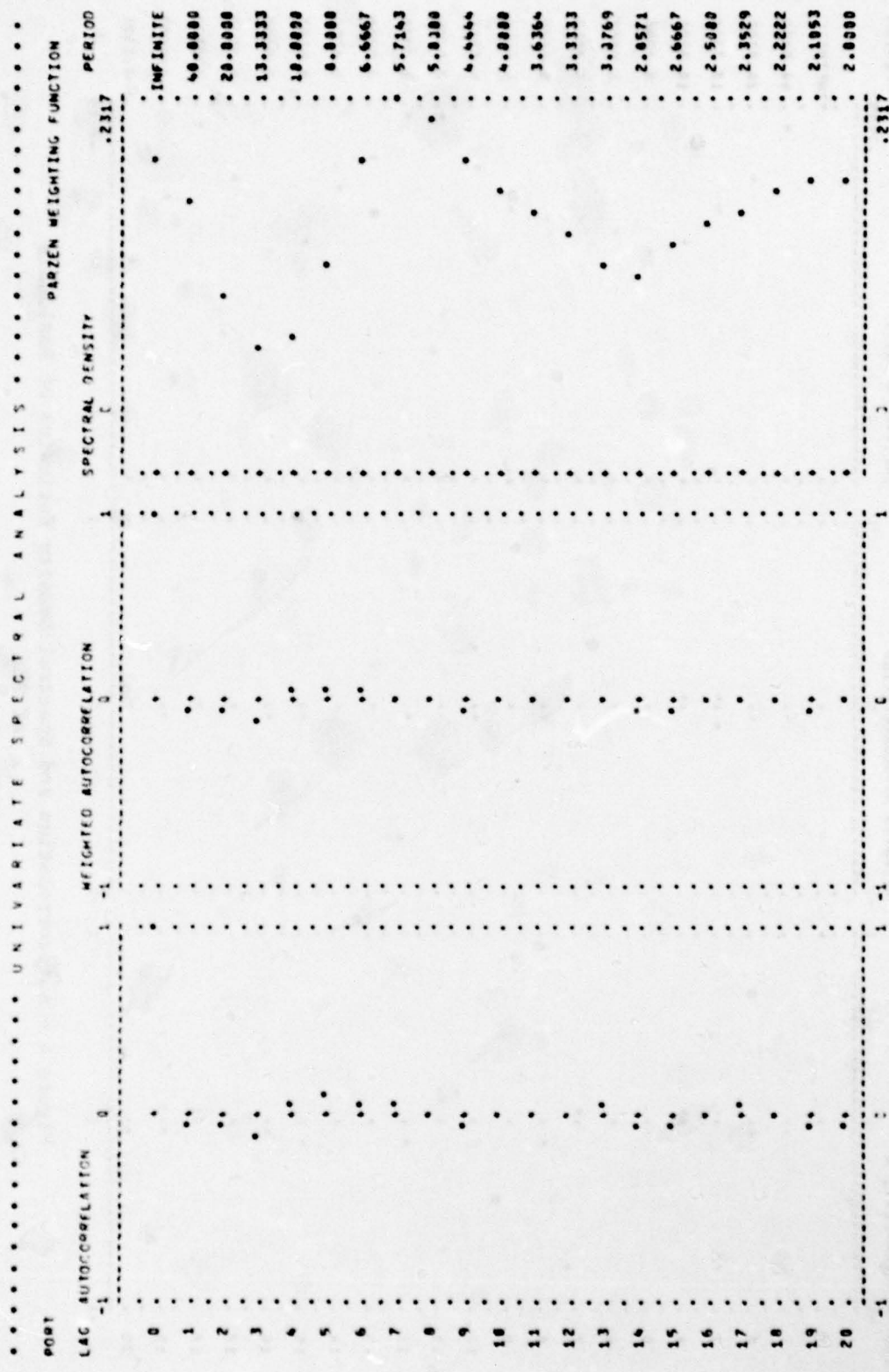


Figure 5 - Autocorrelation and Spectral Density Estimates of Residuals IN PORT

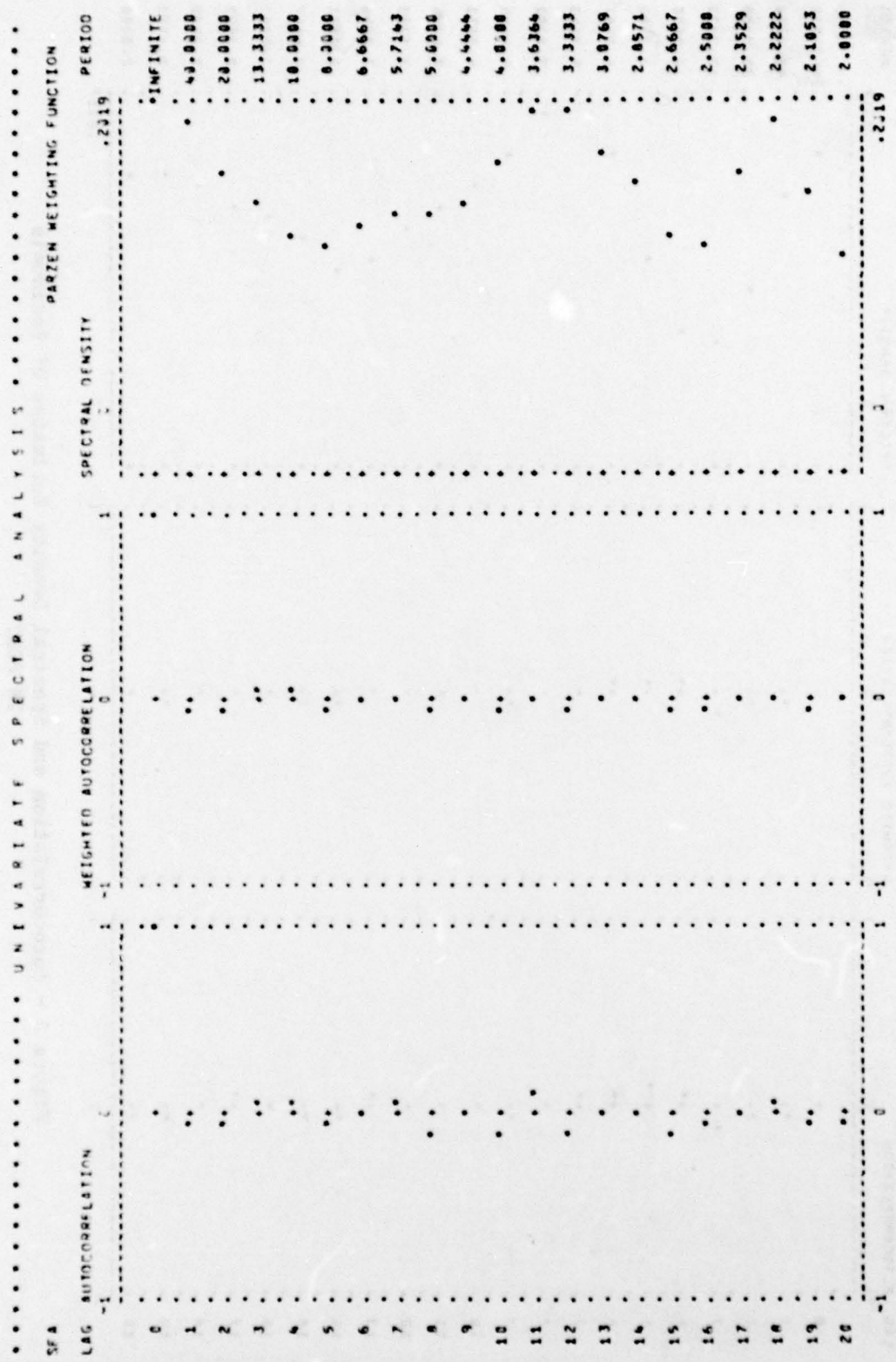


Figure 6 - Autocorrelation and Spectral Density Estimates of Residuals AT SEA

TABLE 4 - AUTOCOVARANCE, AUTOCORRELATION AND SPECTRAL DENSITY ESTIMATES OF RESIDUALS
IN PORT

LAG	SAMPLE UNWEIGHTED	SAMPLE AUTOCOVARANCE UNWEIGHTED	SAMPLE AUTOCORRELATION UNWEIGHTED	SPECTRUM	SPECTRAL DENSITY	LOGARITHMIC SPECTRUM	PERIOD
0	1.95234	1.95234	1.0000	.386698	.1991	-.418396	INFINITE
1	-.58878E-01	-.572601E-01	-.0298	.328377	.1692	-.483627	48.0000
2	-.168967	-.954962E-01	-.0517	.218392	.1119	-.660783	20.0000
3	-.187625	-.165916	-.0960	.156269	.0928	-.806127	13.3333
4	.191824	.148271	-.0927	.108882	.0861	-.774488	10.0000
5	.255012	.193290	-.1366	.256886	.1706	-.593654	8.0000
6	.208531	.129786	.1068	.381187	.1952	-.418862	6.6667
7	.151835	.78779E-01	-.0774	.452442	.2317	-.344437	5.7143
8	.18748E-01	.80459E-02	.0897	.436884	.2223	-.382426	5.0000
9	-.764927E-01	-.251732E-01	-.0392	.385933	.1977	-.613688	4.6464
10	.62165E-01	.154613E-01	.0318	.166903	.1767	-.662302	4.0000
11	.738384E-01	.134570E-01	.0378	.328949	.1644	-.493564	3.6364
12	.16880E-01	.235835E-02	.0811	.295628	.1514	-.529266	3.3333
13	.158957	.136305E-01	.0814	.231716	.1289	-.599898	3.0769
14	-.351821E-02	-.189983E-01	-.0018	.242164	.1248	-.615882	2.8571
15	-.181239	-.316372E-02	-.0519	.277657	.1422	-.556491	2.6687
16	.627518E-01	.652229E-03	.0209	.384103	.1558	-.516979	2.5823
17	.115431	.779157E-03	.0591	.319876	.1634	-.496186	2.3529
18	.323506E-01	.667913E-04	.0171	.382267	.1753	-.465635	2.2222
19	-.743212E-01	-.185803E-04	-.0381	.359999	.1844	-.443698	2.1853
20	-.119977E-01	0	-.0858	.164385	.1866	-.438535	2.0000

OBSERVATIONS 248 MISSING 0 N OF LAGS 20 TIME UNIT MINUTE
 VARIANCE RATIO .374514E-01 DEGREES OF FREEDOM 53 STANDARDIZED BANDWIDTH 1.05433 VARIANCE 1.95238

TABLE 5 - AUTOCOVARANCE, AUTOCORRELATION AND SPECTRAL DENSITY ESTIMATES OF RESIDUALS AT SEA

LAG	SAMPLE UNWEIGHTED	AUTOCOVARANCE WEIGHTED	SAMPLE UNWEIGHTED	AUTOCORRELATION WEIGHTED	SPECTRUM	SPECTRAL DENSITY	LOGARITHMIC SPECTRUM	PARZEN WEIGHTING FUNCTION PERIOD
0	22.2212	22.2212	1.0000	1.0000	6.44695	.2019	.651951	INFINITE
1	-.09737E-01	-.066882E-01	-.0040	-.0040	6.24694	.1911	.628066	40.0000
2	-.120965	-.122967	-.0058	-.0058	3.72793	.1678	.571668	28.0000
3	1.46274	1.27719	-.0649	-.0575	3.27984	.1476	.515853	13.3333
4	1.75682	1.81789	-.0798	-.0638	2.98828	.1343	.474848	10.0000
5	-.817672	-.333358	-.0188	-.0135	2.86882	.1282	.454665	8.0000
6	.223874	.139249	-.0101	-.0063	3.02379	.1361	.480551	6.6667
7	2.64362	1.26728	-.0920	-.0680	3.23163	.1454	.509421	5.7143
8	-1.74923	-.761675	-.0787	-.0334	3.19822	.1436	.503821	5.0000
9	1.10632	.167020	-.0498	-.0165	3.26314	.1469	.513982	4.4444
10	-1.67947	-.619950	-.0756	-.0189	3.90666	.1713	.586567	4.0000
11	3.64866	5.63271	.1391	.0253	4.46873	.2011	.658184	3.6364
12	-1.69690	-.191614	-.0674	-.0086	4.46897	.2011	.658288	3.3333
13	.356528	.195722E-01	-.0168	-.0014	3.95811	.1781	.597518	3.0769
14	.449261	.296622E-01	-.0267	-.0013	3.51857	.1583	.546128	2.8571
15	-1.38757	-.431617E-01	-.0624	-.0020	2.96760	.1335	.472486	2.6667
16	-.387682	-.623227E-02	-.0174	-.0003	2.83843	.1268	.447225	2.5000
17	.609334	.423335E-02	-.0315	-.0002	3.68294	.1657	.566194	2.3529
18	1.63281	.726566E-02	-.0735	-.0001	4.27629	.1926	.631647	2.2222
19	-.54663	-.135112E-03	-.0243	-.0000	3.41621	.1537	.533545	2.1853
20	-.261114	0	-.0314	0	2.65449	.1195	.424845	2.0000

OBSERVATIONS 248 MISSING 3 N OF LAGS 20 TIME UNIT MINUTE
 VARIANCE RATIO .374514E-01 DEGREES OF FREEDOM 53 STANDARDIZED BANDWIDTH 1.85430 VARIANCE 22.2212

TABLE 6 - AUTOCOVARANCE, AUTOCORRELATION AND SPECTRAL DENSITY ESTIMATES OF
IN PORT SIMULATION

UNIVARIATE SPECTRAL ANALYSIS									
LAG	SAMPLE UNWEIGHTED	SAMPLE AUTOCOVARANCE WEIGHTED	SAMPLE UNWEIGHTED	SAMPLE AUTOCORRELATION WEIGHTED	SPECTRUM	SPECTRAL DENSITY	LOGARITHMIC SPECTRUM	PERIOD	PARZEN WEIGHTING FUNCTION
0	1.8654	1.8654	1.8654	1.0000	1.2227	.5493	-.973746E-02	INFINITE	
1	.67524	.68433	.2568	-.2512	.83355	.8763	-.535698E-01	40.000	
2	.516189	.52234	-.2075	-.2720	-.02451	-.2230	-.220377	20.000	
3	.627711	.555681	.3366	-.2979	-.02769	-.2160	-.196364	13.3333	
4	.224841	.181072	-.1266	-.1974	.128491	.1718	-.696105	10.0000	
5	.213979	.153798	-.1147	-.1825	.747621	.1328	-.636213	8.0000	
6	.166837	.103916	-.0895	-.1557	.163568	.0877	-.786382	6.6667	
7	.199249	.104258	-.1468	-.1558	-.115928	.0622	-.935811	5.7143	
8	.26354	.114555	-.1397	-.1592	.138549	.0582	-.964535	5.0000	
9	.11076	.393986E-01	-.6637	-.1211	.134587	.0722	-.970996	4.4444	
10	.179257	.44142E-01	-.5951	-.1240	.196342	.0999	-.729596	4.0000	
11	.427683E-01	.779663E-02	-.223	-.1042	.295314	.1248	-.647264	3.6364	
12	.126811	.162318E-01	-.5880	-.1087	.242463	.130	-.615398	3.3333	
13	-.127360	-.132216E-01	-.6683	-.1059	.267673	.1435	-.572400	3.0769	
14	-.672079E-01	-.254923E-02	-.1253	-.1014	.246317	.1435	-.543153	2.8571	
15	.582344E-01	.141998E-02	-.6312	-.1010	.249849	.1550	-.530368	2.6667	
16	-.125654	-.251111E-02	-.2674	-.1011	.281733	.1511	-.556167	2.5466	
17	.86621E-01	.544336E-03	-.4432	-.1003	.231630	.1242	-.635286	2.3529	
18	.115151E-01	.23225E-04	-.6862	-.1000	.174113	.0934	-.759176	2.2222	
19	.835469E-01	.208867E-04	-.6448	-.1000	.199742	.0913	-.774211	2.1553	
20	.218761E-01	0	-.6117	0	.181938	.0975	-.746677	2.0000	

OBSERVATIONS 240 MISSING 0 N OF LAGS 20 TIME UNIT MINUTE 1.86564
 VARIANCE RATIO .374514E-01 DEGREES OF FREEDOM 53 STANDARDIZED BANDWIDTH 1.85433 VARIANCE 1.86564

TABLE 7 - AUTOCOVARANCE, AUTOCORRELATION AND SPECTRAL DENSITY ESTIMATES OF
AT SEA SIMULATION

UNIVARIATE SPECTRAL ANALYSIS										PARZEN WEIGHTING FUNCTION	
LAG	SAMPLE UNWEIGHTED	SAMPLE AUTOCOVARANCE WEIGHTED	SAMPLE UNWEIGHTED	SAMPLE AUTOCORRELATION WEIGHTED	SPECTRUM	SPECTRAL DENSITY	LOGARITHMIC SPECTRUM	PERIOD			
0	13.4534	13.4534	1.0000	1.0000	5.22782	.3982	.717936	INFINITE			
1	3.01732	3.76292	.2837	.7797	6.72743	.3516	.674625	48.0000			
2	1.67361	1.30186	.1095	.1636	3.71943	.2765	.570519	26.0000			
3	1.01580	1.25339	.1052	.3932	2.88516	.2165	.608170	13.3333			
4	1.01999	1.18735	.1055	.3853	2.51899	.1866	.399865	10.0000			
5	.780694	.561124	.0580	.3417	2.43092	.1607	.385770	8.0000			
6	.967524	.618021	.0719	.2447	2.28258	.1596	.358332	6.6667			
7	1.26029	.628853	.0892	.1466	2.16566	.1618	.335591	5.7143			
8	-.153369	-.652194E-01	-.0114	-.0048	2.12116	.1577	.326573	5.0000			
9	.956552	.316672	.0710	.2235	1.93078	.1495	.285732	4.4444			
10	.230339	.595948E-01	.0177	.0044	1.81507	.1349	.258994	4.0000			
11	.727281E-01	.132547E-01	.0054	.0010	1.87586	.1394	.231196	3.6364			
12	-.167254	-.214090E-01	-.0124	-.0016	1.87635	.1395	.233315	3.3333			
13	-.546002	-.664195E-01	-.0466	-.0335	1.73773	.1292	.239981	3.0769			
14	.606374	.327442E-01	.0451	.0224	1.60466	.1044	.147570	2.8571			
15	1.32094	.612008E-01	.0982	.0331	1.89581	.0815	.373444E-01	2.6667			
16	.251535	.432455E-02	.0187	.0003	1.46697	.0853	.595511E-01	2.5360			
17	-.105044	-.714448E-03	-.0079	-.0001	1.37123	.1319	.137110	2.3529			
18	.71333	.162666E-02	.0530	.0001	1.34943	.1033	.142838	2.2222			
19	.799731	.199333E-03	.0594	.0000	1.19120	.0875	.759848E-01	2.1053			
20	.271287	0	.0202	0	1.06726	.0793	.282729E-01	2.0000			

OBSERVATIONS 248 MISSING 0 N OF LAGS 20 TIME UNIT MINUTE
 VARIANCE RATIO .374514E-01 DEGREES OF FREEDOM 53 STANDARDIZED BANDWIDTH 1.45433 VARIANCE 13.4534

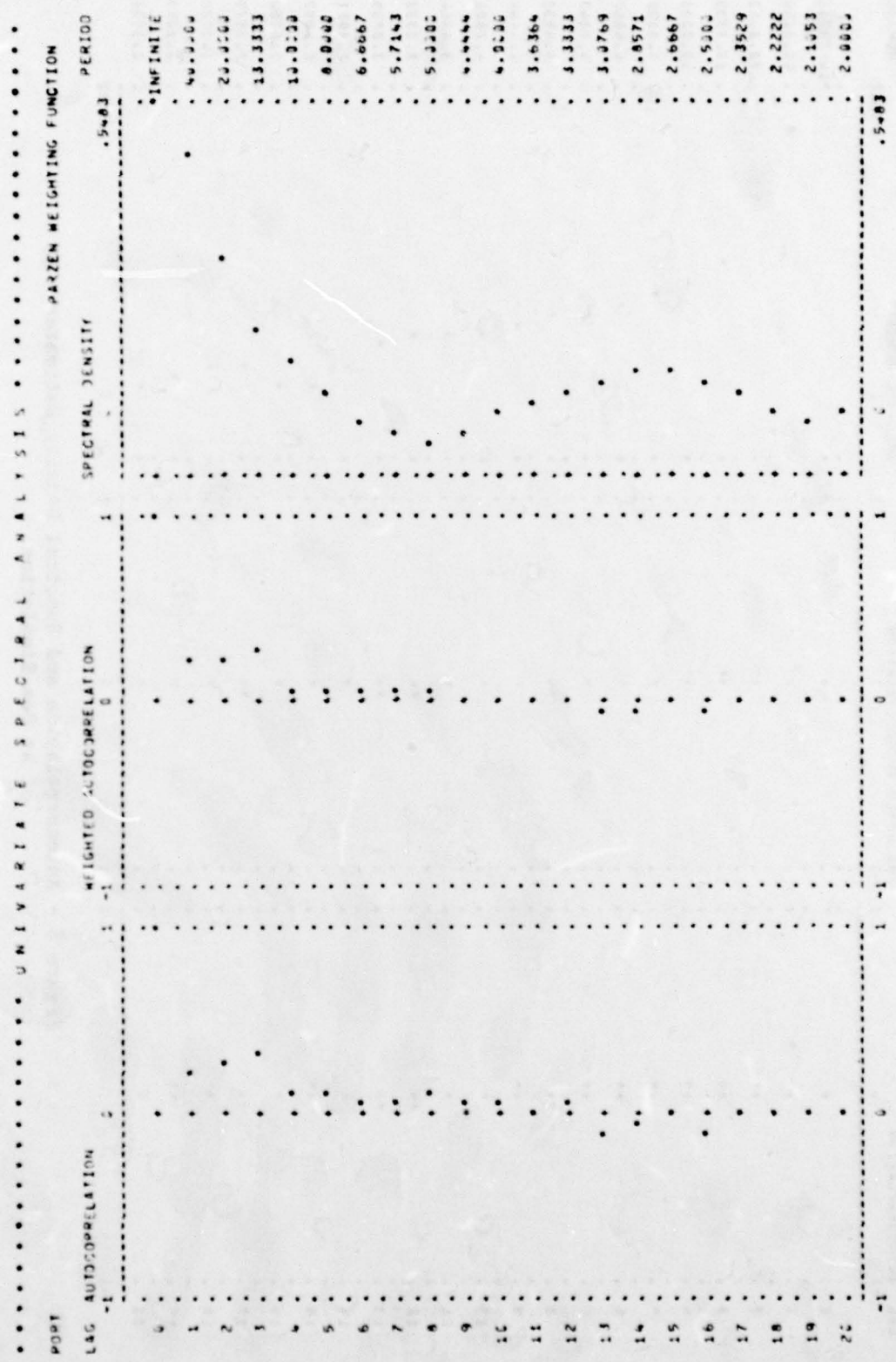


Figure 7 - Autocorrelation and Spectral Density Estimates of In Port Simulation

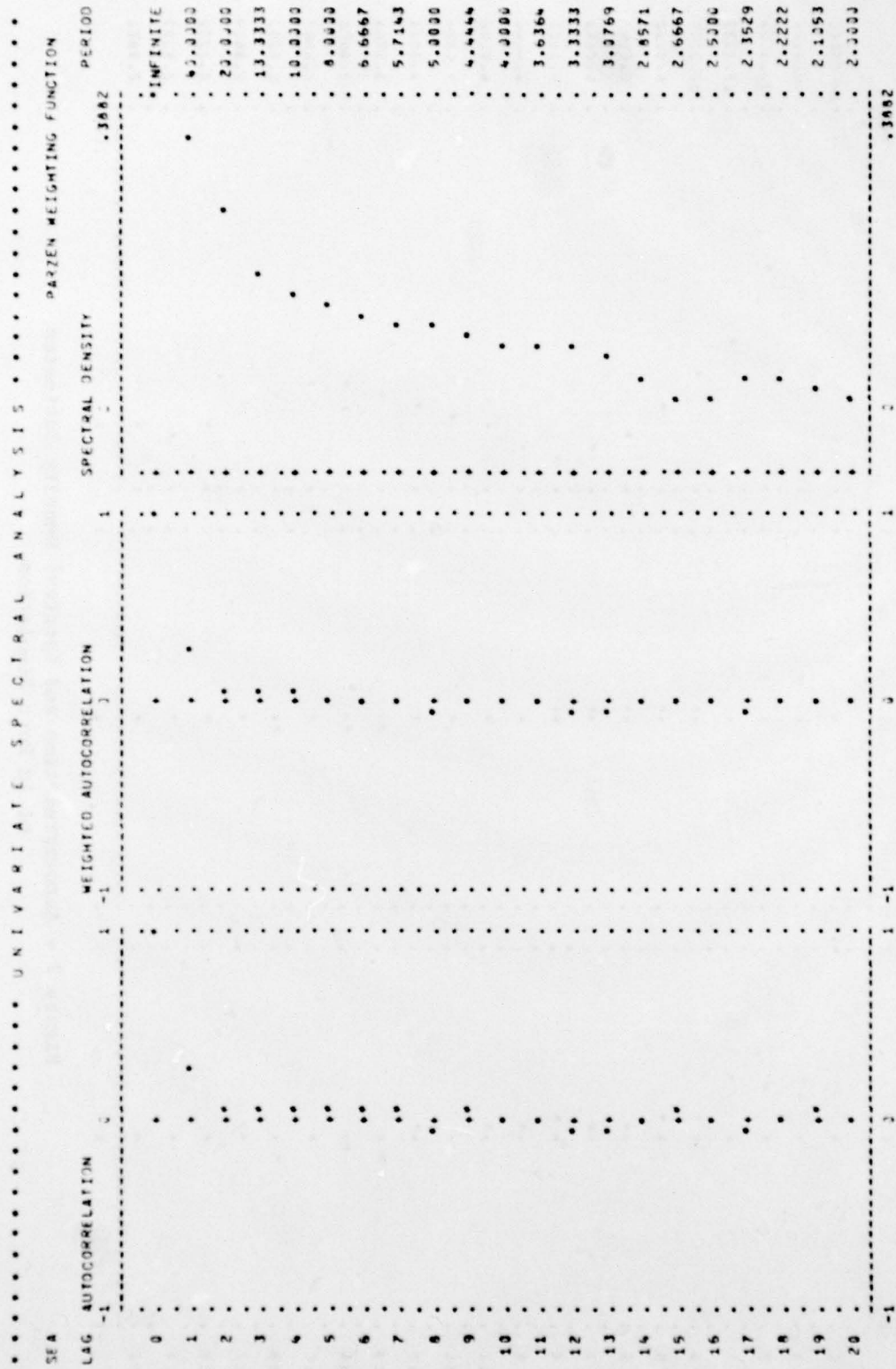


Figure 8 - Autocorrelation and Spectral Density Estimates of At Sea Simulation

concluded that the truncation function produces the apparent periodicities indicated in the spectral estimates of the residuals and no expansion of model forms is required.

MODEL EXTRAPOLATION TO FLEET

Although the flow fluctuation models developed in the previous sections are sufficient to characterize the Aft Head sewage flow rate onboard the USS HAROLD J. ELLISON, these models would be of little use unless some method is available which would allow application to other ships of the U.S. Navy Fleet. This section provides such a methodology and states the assumptions under which this extrapolation is valid.

The Aft Head source data on which the models are based consist of the volumes of combined commode and urinals flush water. Since flush water is directly related to complement, shipboard crew size information should be the principal extrapolation factor, assuming that crew habits and the quantity of water released per flush are consistent on a fleetwide basis. A standard practice is to repair/replace poorly maintained flushometers prior to the start of a NEPSS Shipboard Survey so that a consistent flush volume can be maintained and valid comparisons can be made among surveyed ships.

The second assumption, the fleetwide consistency of the crew's daily sanitary habits, is presumed to be reflected in the autocorrelation function pattern of the data. On a fleetwide basis in-port sewage generation is represented by an AR(3) process with the ϕ_i , $i=1,2,3$ values as displayed in Table 3, and at-sea generation by AR(1) with $\phi_1 = 0.252$. Crew habits, however, are difficult to verify and consistency must be presumed for extrapolation purposes.

Under these assumptions, the only adjustments required to the parameter values of the models are for c and σ_a^2 . These two parameters can be made dependent on ship's population level in the following manner: c and σ_a^2 are related to MEAN and VAR of Table 3 by the formula

$$c = \text{MEAN} \times (1 - \phi_1 - \phi_2 - \dots - \phi_p)$$
$$\sigma_a^2 = \text{VAR} \times (1 - \phi_1 r_1 - \phi_2 r_2 - \dots - \phi_p r_p)$$

where the r_k are functions of the ϕ_i 's only. MEAN and VAR values obtained from the Aft Head of the ELLISON may be reduced to 15-minute, per capita values by the method shown in Table 8. The results of Table 8 rest on the assumption that the ratio of Aft Head flow to Total Salt Water flow is equivalent to the ratio of Aft Head users to Total Ship population. This assumption is plausible since the total salt water flow consists of all commode and urinal flow on the ELLISON (including Forward Crew's Head and Officer's Head) as measured by survey over a 5-month period. It is also assumed that there is inconsequential head area crossover usage between Aft Crew, Forward Crew, and Officer Quarters. As a consequence, under the assumptions stated, designated model parameters can be adjusted to reflect changes in ships' force level.

To demonstrate the procedure, model parameters will be extrapolated to reflect the sewage generated by total crew of the ELLISON.

With an Average Total Ship's Crew of 135 in port and 205 at sea, we have

At Sea

$$\text{MEAN} = 205 \times 0.0268 = 5.494 \times 10^{-1} \text{ gallons/15 min.}$$

$$\text{VAR} = (205)^2 \times 13.6823 \times 10^{-4} = 57.500 \times (10^{-1} \text{ gallons/15 min.})^2$$

$$C = \text{MEAN} \times (1 - \phi_1) = 5.494(1 - 0.252) = 4.110 \times 10^{-1} \text{ gallons/15 min.}$$

$$\sigma_a^2 = \text{VAR} \times (1 - \phi_1^2) = 57.500 \times [1 - (.252)^2] = 53.849 \times (10^{-1} \text{ gallons/15 min.})^2$$

In Port

$$\text{MEAN} = 135 \times 0.01517 = 2.048 \times 10^{-1} \text{ gallons/15 min.}$$

$$\text{VAR} = (135)^2 \times 3.1708 \times 10^{-4} = 5.779 \times (10^{-1} \text{ gallons/15 min.})^2$$

$$C = \text{MEAN} \times (1 - \phi_1 - \phi_2 - \phi_3) = 2.048 \times (1 - 0.278 - 0.109 - 0.161) = 0.930 \times 10^{-1} \text{ gallons/15 min.}$$

$$\sigma_a^2 = \text{VAR} \times (1 - \phi_1 r_1 - \phi_2 r_2 - \phi_3 r_3) = 5.779 [1 - (0.278)(0.349) - (0.109)(0.206) - (0.161)(.256)] = 4.850 \times (10^{-1} \text{ gallons/15 min.})^2$$

where $r_1 = (\phi_1 + \phi_2 \phi_3) / (1 - \phi_2 - \phi_1 \phi_3)$

$$r_2 = \phi_1 r_1 + \phi_2$$

$$r_3 = \phi_1 r_2 + \phi_2 r_1 + \phi_3$$

TABLE 8 - PER CAPITA MEAN AND VAR ESTIMATES
FOR MODEL APPLICATION

	In Port	At Sea
Aft Head Gallons/Day ¹	1664.9	3181.0
Total Saltwater Gallons/Day ¹	2587.8	4929.4
Ratio	0.643	0.645
Average Total Ship's Crew	135	205
Estimated Aft Head Users ²	87	132
15 minute MEAN (TABLE 3)	1.32	3.54
15 minute VAR (TABLE 3)	2.40	23.84
15 minute MEAN/CAPITA ³	0.01517	0.0268
15 minute VAR/CAPITA ⁴	3.1708×10^{-4}	13.6823×10^{-4}

¹Averages from 5 month survey.

²Ratio \times Average Total Ship's Crew.

³15 minute MEAN/Estimated Aft Head Users
(in units of 10^{-1} Gallons/Capita)

⁴15 minute VAR/(Estimated Head Users)²
in units of $(10^{-1}$ Gallons/capita)²

REFERENCES

1. Box, G.E.P. and G.M. Jenkins, "Time Series Analysis Forecasting and Control," revised edition, Holden-Day, Inc., San Francisco (1976).
2. "The IMSL Library Reference Manual," International Mathematical and Statistical Libraries, Inc., Houston, Texas (July 1977).

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APPENDIX
Baseline Flow Data Listing

TIME OF DAY	AT SEA			IN PORT		
	DAY			DAY		
	(1)	(2)	(3)	(1)	(2)	(3)
0015	3	9	2	0	0	0
0030	2	0	10	0	1	0
0045	1	1	0	0	0	1
0100	1	0	0	0	0	0
0115	1	1	3	0	0	0
0130	0	3	2	0	0	0
0145	0	14	14	0	0	2
0200	0	0	5	0	0	0
0215	0	0	0	0	1	0
0230	0	20	2	0	0	0
0245	0	7	1	1	0	0
0300	0	0	0	1	0	0
0315	1	0	0	0	0	0
0330	0	2	0	0	0	0
0345	1	1	0	0	0	0
0400	11	6	4	0	0	1
0415	0	0	1	1	1	0
0430	0	0	5	0	0	0
0445	0	0	3	0	0	0
0500	0	0	0	1	0	0
0515	0	0	0	0	1	1
0530	9	1	0	0	0	0
0545	0	4	1	1	0	0
0600	0	3	0	2	0	0
0615	1	9	0	1	0	0
0630	2	0	0	0	0	0
0645	5	6	0	4	0	3
0700	3	1	1	1	0	4
0715	3	9	22	2	7	6
0730	1	3	6	2	0	2
0745	3	10	2	3	3	1
0800	6	5	2	3	2	4
0815	5	2	5	2	2	3
0830	1	12	7	2	4	3
0845	1	3	0	2	0	3
0900	2	12	2	1	5	3
0915	1	9	2	0	3	5
0930	3	0	0	0	2	1
0945	3	1	1	0	4	2
1000	7	1	14	0	1	3
1015	5	1	10	0	2	2
1030	2	1	0	1	6	2
1045	0	1	0	0	3	1
1100	5	1	1	1	2	2
1115	11	0	0	1	3	3
1130	2	1	5	0	3	1
1145	0	6	16	2	1	1
1200	5	2	1	3	4	1

TIME OF DAY	AT SEA			IN PORT		
	DAY			DAY		
	(1)	(2)	(3)	(1)	(2)	(3)
1215	11	5	1	1	5	2
1230	13	17	23	1	1	2
1245	23	7	15	1	2	4
1300	11	0	2	2	5	5
1315	6	2	0	2	2	0
1330	0	4	7	2	1	1
1345	0	8	11	3	2	1
1400	0	16	0	1	2	2
1415	0	19	11	5	3	3
1430	0	3	0	3	1	1
1445	7	10	17	1	1	1
1500	7	10	0	1	0	0
1515	0	3	2	2	3	1
1530	5	0	1	1	0	1
1545	0	2	0	1	2	11
1600	9	2	2	0	0	1
1615	5	1	0	1	5	2
1630	11	7	0	1	4	1
1645	0	6	5	3	1	2
1700	1	5	7	1	1	5
1715	1	0	1	0	2	1
1730	3	6	7	2	4	2
1745	1	5	4	2	3	2
1800	2	7	2	0	2	1
1815	6	13	2	1	1	4
1830	1	0	0	2	2	4
1845	2	0	1	2	1	1
1900	2	0	1	3	0	0
1915	24	1	0	1	1	1
1930	12	0	1	1	0	2
1945	7	3	1	2	0	2
2000	6	6	1	1	0	1
2015	9	2	0	0	2	1
2030	2	0	0	0	0	1
2045	1	0	0	1	0	0
2100	15	7	0	0	1	0
2115	11	0	1	1	1	2
2130	9	0	2	2	3	2
2145	0	14	0	1	1	2
2200	0	1	0	1	0	2
2215	0	1	0	0	0	0
2230	0	1	4	1	1	0
2245	0	1	1	0	2	1
2300	0	1	0	0	0	0
2315	0	0	0	1	0	1
2330	2	0	0	1	1	0
2345	0	2	0	0	1	1
2400	1	4	0	2	0	1

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