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Prepared by

Information Systems Laboratory
Digital Systems Laboratory
Integrated Circuits Laboratory
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ILLUSTRATIONS

I. INFORMATION SYSTEMS

A. Project 6151. STATISTICAL DATA PROCESSING AND PATTERN RECOGNITION

Principal Investigator: T. M. Cover
Staff: R. King, A. El Gamal, K. Jarett,
J. van Campenhout, M. Salehi

1. Objective

The purpose of this project is to investigate problems of information processing and pattern recognition.

2. Current Status of Work

a. The Measurement-Selection Problem in Regression Analysis (J. van Campenhout)

The similarity between measurement selection in linear regression and in two-class common covariance gaussian classification problems has been developed. Based on earlier results obtained from measurement selection in classification problems, it can be concluded that optimal subset-selection algorithms must be exhaustive in regression problems with vector-valued regressors.

It is also proved that the subclass of regression problems with scalar regressors cannot induce all monotone orderings on regressor subsets. It is possible, therefore, that nonexhaustive optimal search algorithms exist for this class of problems.

b. Resolution of the Hughes Paradox (J. van Campenhout)

Various researchers have observed that, in some cases, the Bayes recognition accuracy of pattern classifiers peaks with increasing measurement complexity. This result is apparently paradoxical because more complex measurements should reduce the misclassification probability.

This problem has been investigated, and it has been verified that the paradoxical peaking effect is caused by incorrect comparisons of statistically incomparable models. A formalization of comparability has been introduced, some of the results obtained in the literature have been analyzed, and a paper will be published.

c. Practical Application of Superposition Codes (K. Jarett)

Preliminary results indicate that superposition codes require roughly the same decoding complexity as do random codes, given a fixed probability of error requirement.

Superposition codes are attractive because their complexity grows only linearly with rate. Instead of using a rate R random code with 2^{nR} codewords, an L-stage superposition code in which $L = R/R_0$ can be applied, and each stage has R_0 and 2^{nR_0} codewords. The decoder need only be capable of L consecutive maximum-likelihood decodings in a codebook of 2^{nR_0}. The problem is that, for a given block length n, the superposition code has a much higher error probability.

For large n, exponential error-probability bounds in the form of $2^{-n(C-R)}$ show that a 1-stage $R = \sum_1^L R_i$ superposition code requires a block length of nL to equal the error probability of a block length n rate R random code. For this superposition code,

$$P_e \leq \sum_1^L 2^{-(nL)(C_i - R_i)} = L2^{-nL\left(\frac{C}{L} - \frac{R}{L}\right)} = L2^{-n(C-R)} \sim 2^{-n(C-R)}$$

if $C_i = C/L$ and $R_i = R/L$ for all i; otherwise, the error bound is worse. With a block length nL and $R_i = R/L$, each stage of the superposition code has a codebook of $2^{(nL)R_i} = 2^{nR}$. As a result, for either superposition or ordinary random codes (given a fixed P_e), the decoder must be capable of a maximum-likelihood decoding in a codebook of 2^{nR}.

Numerical results obtained for the binary symmetric channel confirm these theoretical estimates.

d. Multiple-Access Channels with Generalized Feedback (R. King)

An achievable rate region has been determined for multiple-access channels with generalized feedback--feedback not necessarily equal to but correlated with the channel output. Noiseless feedback increases the capacity of a multiple-access channel and is a special case of generalized feedback.

The theory of coding with side information was used to extend noiseless feedback to generalized feedback. The new achievable rate region yields the total cooperative rate region for several non-trivial examples.

e. Multiple-Access Channels with Correlated Sources and Feedback (R. King)

Consider a multiple-access channel with sources correlated in a special manner. Each transmitter observes one independent source (as in the standard multiple-access channel); in addition, however, both transmitters observe a third source in common, and the capacity of this channel is a known result.

An achievable rate region has been derived for this channel with noiseless feedback added. New intuition into the relationship between the known results for multiple-access channels with correlated sources and with feedback is thus gained.

f. Bounds on Cardinality of Auxiliary Random Variables in Multiuser Communication Channels (M. Salehi)

The method of Ahlswede and Korner has been employed to determine the upper bounds on the cardinality of auxiliary random variables involved in the description of capacity regions for multiuser channels. Some of the existing bounds have been improved.

Bounds have been successfully obtained in the following cases:

- source coding with side information
- more capable broadcast channels
- broadcast channels with degraded message sets
- multiple-access channels with correlated sources
- multiple-access channels with feedback
- common information of two random variables

g. Capacity of the Product and Sum of Two Inconsistently Degraded Broadcast Channels (A. El Gamal)

Let $p(y_1,z_1|x_1) = p(y_1|x_1)\, p(z_1|y_1)$ and $p(y_2,z_2|x_2) = p(z_2|x_2)\, p(y_2|z_2)$ be two degraded broadcast channels. The broadcast channel with sender X_1,X_2 and receivers Y_1,Y_2 and Z_1,Z_2 is referred to as the product of two inconsistently degraded broadcast channels.

Similarly, the sum of two inconsistently degraded broadcast channels is defined as the broadcast channel with $X_1 \cup X_2$ as sender and $Y_1 \cup Y_2$ and $Z_1 \cup Z_2$ as receivers. In contrast to the two degraded broadcast channels, the sum and product channels are not degraded.

Capacity regions have been established for the

- discrete memoryless product of two inconsistently degraded broadcast channels
- spectral gaussian broadcast channel
- discrete memoryless sum of two inconsistently degraded broadcast channels

These capacity theorems include the partial results obtained by Poltyrev for the discrete memoryless product channel and by Hughes-Hartogs for the spectral gaussian broadcast channel, and they prove that the Hughes-Hartogs rate region is optimal for the zero common-rate case. A paper has been submitted to Problemy Peredaci Informacci.

h. Capacity of a Class of Broadcast Channels (A. El Gamal)

The capacity region has been determined for any discrete memoryless broadcast channel $p(y,z|x)$ for which $I(X;Y) \geq I(X;Z)$ for all input distributions. This region resembles the capacity region for degraded message sets considered by Körner and Marton. A paper has been accepted for publication in IEEE IT.

i. Capacity Theorems for the Relay Channel (T. Cover, A. El Gamal)

A relay channel consists of an input x_1, relay output y_1, channel output y, and relay sender x_2 (whose transmission depends

on the past symbols y_1). The dependence of the received symbols on the inputs is $p(y,y_1|x_1,x_2)$. The channel is assumed to be memoryless.

The following capacity theorems have been proved:

if y is a degraded form of y_1, then

$$C = \max_{p(x_1,x_2)} \min \left[I(X_1,X_2;Y), I(X_1;Y_1|X_2) \right]$$

if y_1 is a degraded form of y, then

$$C = \max_{p(x_1)} \max_{x_2} I(X_1;Y|x_2)$$

if $p(y,y_1|x_1,x_2)$ is an arbitrary relay channel with feedback from (y, y_1) to both x_1 and x_2, then

$$C = \max_{p(x_1,x_2)} \min \left[I(X_1,X_2;Y), I(X_1;Y,Y_1|X_2) \right]$$

A superposition-block Markov encoding shows the achievability of C, and converses are established. The capacities of the gaussian relay channel and certain discrete relay channels have been evaluated, and a lower bound on the capacity of the general relay channel has been established. A paper has been submitted to IEEE IT.

B. Project 6240. OPTIMAL CODES WITH VARIABLE WEIGHT SYMBOLS

Principal Investigator: J. Gill
Staff: N. Cot

1. Objective

The objectives of this project are to determine procedures for producing optimal uniquely decipherable codes, using symbols of unequal costs, and to study the properties of optimal codes.

2. Current Status of Work

We have demonstrated that variable-length coding schemes can be applied to several fields other than communications, including

- game theory where they are associated with the determination of optimal gambling strategies
- data allocation in storage and data retrieval [1] where their application is based on the relationship between double-chained trees and variable-length codes; a file can be organized as a double-chained tree in which keys correspond to variable-length codewords

An optimal tree (or code) corresponds to a minimal average search time. If $0 < b_1 < b_2 \ldots < b_t$ are the costs of the symbols of a code alphabet and λ is determined by

$$\lambda^{-b_1} + \lambda^{-b_2} + \ldots + \lambda^{-b_t} = 1$$

then the converse to the source-coding theorem establishes a lower bound on the average cost $\bar{c}$ of a code $\{w_1,\ldots,w_n\}$ with codeword probabilities $\{p_1,\ldots,p_n\}$,

$$\bar{c} \geq \frac{H(p_1, \ldots, p_n)}{\log_2 \lambda}$$

where $H(p_1,\ldots,p_n)$ is the entropy (in bits) of the probability distribution $p_1,\ldots,p_n$.

We have also determined an upper bound on the cost of optimal codes,

$$\bar{c} < \frac{H(p_1, \ldots, p_n)}{\log_2 \lambda} + b_1 + \delta$$

where $\delta \leq b_t$ is a quantity calculated from $b_1,\ldots,b_t$. Using this upper bound, nearly optimal codes can be realized for unequal probabilities.

For equiprobable codewords, a procedure for producing optimal codes has been analyzed [2] and shown to require $O(\log^t n)$ steps to produce optimal codes with n codewords, and the cost of these codewords was determined in Reference 3. This procedure is being extended to nearly equiprobable codewords.

References

1. L. Stanfel, "Optimal Trees for a Class of Information Retrieval Problems," Info. Stor. Retr., 9, 1973, pp. 43-59.

2. N. Cot, "The Complexity of the Variable-Length Encoding Problem," Sixth Southeastern Conference on Combinatorics, Graph Theory, and Computing, 1975.

3. N. Cot, "Cost of Optimal Prefix Codes," Johns Hopkins Conf. on System Sciences, Apr 1977.

C. Project 6302. PROBLEMS IN CONTROL

Principal Investigator: G. F. Franklin
Staff: S. Shah

1. Objective

This study is concerned with design problems in automatic control systems, especially under conditions of model uncertainty.

2. Current Status of Work

The characteristics of the self-tuning regulator have been studied, plus related schemes for simultaneous identification and control. The goal is to develop an algorithm for adaptive control which will apply to multivariable processes that may be nonminimum phase.

The following guidelines have been established.

- The structure of the model must be selected to produce simple identification and control algorithms simultaneously. In the self-tuning regulator, an ARMA model with least-square identification and minimum-response squared error constitutes such a structure; however, in the multivariable case, the solution is not yet known.

- The requirements for the convergence of the identification algorithm can be weak. Because the algorithm is to be used for control, the self-correcting nature of the control action reduces the restrictions on parameter accuracy.

- Inclusion of forced delay in the model may be able to account for the nonminimum-phase characteristics of the plant.

- Control algorithms must be developed, which are easily implemented with varying plant parameters but still allow for constraints on the control effort.

D. Project 6502. DATA-COMPRESSION TECHNIQUES AND APPLICATIONS

Principal Investigator: R. M. Gray
Staff: Y. Linde, Y. Matsuyama

1. Objective

The objective of this work is to develop nearly optimal moderately complex data-compression algorithms. The primary focus is on tree and trellis coding techniques. Common random process models and real speech data are considered.

2. Current Status of Work

This project is concerned with the development and simulation of time-invariant nonlinear digital filters to be used as decoders in a tree or trellis data-compression system having a matched tree search algorithm (such as a Viterbi or M algorithm) as encoder. A technique called the "fake process" approach was developed wherein one first attempts to simulate or "fake" a given source by time-invariant nonlinear digital filtering a memoryless binary source. If a filter provides a good fake process, it will also perform well as the decoder of a tree data-compression system. The following technique was developed to produce the desired fake.

The register containing the binary digits was considered as a digital representation of a real number between 0 and 1. This number was passed through a "scrambler" or mapping from (0,1) to (0,1) and then

through an inverse-distribution function mapping corresponding to the marginal distribution of the original source. With the correct scrambler and by following the inverse distribution by a linear digital filter, the marginal distribution of the source can be approximated and the power spectral density matched exactly. This technique led to one-bit-per-symbol data-compression systems that outperformed traditional systems by 1 to 2 dB for gaussian sources with and without memory.

These techniques have been extended to "pseudo-speech" models consisting of autoregressive filters driven by white Laplacian noise and then to real speech data obtained from standard reference files. The pseudo-speech experiment was completed, and performance of 0.5 to 1 dB better than predictive quantization was obtained (predictive quantization operates well on autoregressive models). The system for compressing real speech has been completed, and we are testing several adaptive and nonadaptive fake-process tree coders on real speech. Initial results indicate that a 9 dB SNR is obtainable at 8000 bits/sec; this performance is superior to most waveform coders but inferior to LPC and APC techniques. Because this system is a first attempt, several possibilities for improvement are being considered.

This project is also supported by the Air Force Office of Scientific Research.

E. Project 6601. INFORMATION THEORY AND INFORMATION PROCESSING

Principal Investigator: M. E. Hellman
Staff: R. Kahn, D. Andelman

1. Objective

The objective of this project is to investigate the relationships between information theory, information processing, and complexity theory.

2. Current Status of Work

A paper entitled The Wiretap Channel with Feedback is being prepared. The central problem is confidential communication over

multiuser information channels. The secrecy rate is defined as the average equivocation of information at the eavesdropping terminal (on a per transmission basis), which is common to both of the legitimate users--including the message information to be transmitted between them and any residual randomness that may occur in the channel. A procedure has been developed wherein it is possible to extract from the common information a totally secret message (or key) which is independent of the main message. This secret key can be exclusive-Ored with the main message, which otherwise would be inadequately protected by standard wiretap encoding.

In addition to using this technique to increase message equivocation when transmitting on a block-by-block basis, it is also a very effective procedure when time-sharing between two modes of operation--one with a high key-generation rate and the other with a high message-transmission rate. A very simple relationship has been observed between the set of achievable rate-secrecy pairs (R,S) and the corresponding set of achievable rate-equivocation pairs (R,R_e); the latter is an alternate but equivalent description of the (R,d) region. Based on this formalism, the paper will describe an achievable key-generation rate (assuming public feedback) and improved regions for the independent binary erasure and independent binary symmetric wiretap channels.

A long-held belief that Slepian-Wolf feedback is optimal has been proven false by counterexample. We are also extending the wiretap channel with feedback to a two-way channel with eavesdropper. In addition, the feasibility of a convolutional wiretap encoder has been studied, but no definite results have been obtained.

F. Project 6701. THE RECURSIVE-FILTER ADAPTIVE LINE ENHANCER[†]

Principal Investigator: B. Widrow
Staff: P. Thompson

1. Objective

The adaptive line enhancer (ALE), consisting of a digital filter adapted to produce a minimum mean-squared-error prediction of a future

[†]This work is supported partially by the United States Department of Energy.

input, has proven to be a useful tool for detecting narrowband signals obscured by wideband noise and for estimating the spectral characteristics of signals. Earlier research has provided a good basis for understanding the behavior of the ALE when the adaptive filter is constrained to an all-zero tapped-delay-line (TDL) configuration. It is widely recognized that a recursive filter, containing both poles and zeros, can perform better with a smaller number of parameters than an all-zero filter; however, procedures for adjusting these parameters are not well established. The objective of this research, therefore, is to develop and analyze appropriate adaptation algorithms for a recursive-filter adaptive line enhancer.

2. Current Status of Work

Several algorithms are being analyzed and compared. All are based on the well-known relationship between the optimal filter for estimating a signal in white noise and the corresponding inverse filter that whitens the observed process. This relationship makes adaptive filtering an adaptive inverse-modeling problem encountered in other such disciplines as system identification and time-series analysis.

The most general of the algorithms being considered is an approximate maximum-likelihood scheme similar in structure to an extended Kalman filter. The gradient of the mean-squared value of the inverse-filter output (residual) with respect to the vector of adjustable filter parameters, plus an inverse covariance matrix, is approximated from filtered inputs and residuals to update the parameters. The filters used for computing the updates consist of the pole-only portion of the adaptive inverse filter which changes during adaptation--hence, the approximate nature of the algorithm.

The computations per iteration required for this algorithm are $0(n^2)$, where n is the number of poles plus the number of zeros. This can be reduced to $0(n)$ by replacing the covariance matrix with its trace; however, the price paid for this reduction is an increase (particularly at low signal-to-noise ratios) in the number of iterations required for adaptation. Compromise methods are being sought to produce fast adaptation with minimum computation per iteration. In addition, the trade-offs

between adaptation time and signal-estimation error are being studied experimentally and analytically.

When signals are sinusoidal or very narrowband (with respect to the Nyquist rate), the most promising of the adaptation techniques is a bootstrap method wherein only the feedforward parameters are adapted, and the feedback parameters are slaved to the feedforward parameters so that the poles (in the inverse filter) are slightly closer to the origin in the z-domain than are the zeros, thereby facilitating the desired notch in the inverse filter and peak in the signal-estimation filter. This preselected relationship between poles and zeros constrains the filter away from the optimal solution by setting the minimum attainable bandwidth, but it has been demonstrated in simulations that, for a sinusoidal signal, the constrained filter performs as well or better than the unconstrained filter when algorithm gains are adjusted to produce comparable convergence times. It has also been observed that the performance of the bootstrap recursive filter is comparable to a TDL filter with similar bandwidth capabilities. Because the bandwidth in the recursive filter is not coupled to the number of parameters as it is in the TDL, the recursive filter is superior in terms of computations per iteration. Quantification of these results and characterization in other respects are being analyzed.

G. Project 7050. STUDIES IN STATISTICAL SYSTEM THEORY

Principal Investigators: T. Kailath, M. Morf
Staff: J. Dobbins, D. Lee, B. Lévy, J. Newkirk, G. Verghese, E. Verriest

1. Objective

The purpose of this project is to analyze the basic problems in statistical system theory.

2. Current Status of Work

a. Generalized State-Space Systems (T. Kailath, G. Verghese, B. Lévy)

Research has focused on identifying and eliminating difficulties encountered during earlier treatments of systems in the form

of $E\dot{x} = Ax + Bu$, where E is a square but singular matrix. Our work has led to a better understanding of the special properties of such system descriptions, methods for analyzing and transforming them, and their significance in practical applications. Generalized state-space descriptions of the above form are common when the governing equations are written in terms of the "natural" system variables. They appear when describing the interconnection of subsystems to form composite systems and, in this respect, they are particularly significant when displaying the structure of LCR networks; they also appear in the analysis of singularly perturbed dynamic systems.

The distinguishing feature of such systems is that they can exhibit an impulsive response to arbitrary initial conditions at $t = 0-$ which corresponds to natural frequencies at <u>infinity</u>. The reason for this is that the matrix $sE - A$ (which determines natural frequencies) loses rank not only for a set of finite values of s but also for infinite s.

Such behavior does not appear to have been considered before, perhaps because, if the system is in operation prior to $t = 0$, initial conditions must satisfy the system equations and cannot be arbitrary; the resulting constraints guarantee that impulsive behavior will not occur. Several problems appear, however, when the system is formed only at $t = 0$ (as a result of the composition of subsystems or component failure). As with LCR networks, the essential structure may be such that, <u>if</u> assembled at $t = 0$ with arbitrary initial conditions, its behavior is impulsive or, in singularly perturbed structures, the limiting singular problem may already be a generalized system with arbitrary initial conditions.

For such systems, we have defined a generalized system order, developed concepts of controllability and observability "at infinity," and generated transformations to obtain equivalent systems. Several interesting results can now be obtained in this framework.

b. <u>Square-Root Algorithms for Parallel Processing</u> (M. Morf, J. Dobbins, J. Newkirk, T. Kailath)

With time-invariant systems, our previously reported parallel-processing results yield an algorithm that calculates

$P^{1/2}(t), P^{1/2}(2t), P^{1/2}(4t), \ldots$ on successive iterations, where P is the matrix Riccati variable. This rapid method of calculating the steady-state Riccati solution is valuable when synthesizing constant-parameter filters or controllers. A computer implementation has been written and debugged. It has performed well on a variety of test problems, including some for which competitive algorithms based on an eigenvector decomposition of the associated Hamiltonian system have failed to converge.

Parallel-processing results have been obtained when the available information is the covariance of the process under observation rather than a state-space model generating the process. Realizing these algorithms in square-root form appears to require "square roots" of indefinite matrices. Factorizations in the form of $M = A \Sigma A'$ can be used, where Σ is a signature matrix, and transformations T (such that $T \Sigma T' = \Sigma$) have been developed for updating the factors. The numerical stability of these transformations, however, remains to be verified, and interpretation of the factors is still in question. The standard square-root arrays may be interpreted as arrays expressing certain estimate errors in terms of orthonormal bases. Analogous interpretations of the $A \Sigma A'$ factorizations would require basis random variables with negative covariances. A more satisfactory explanation should result from the following work.

c. More General Array Methods for Least-Squares Estimation (J. Dobbins, T. Kailath)

Factorizations in the form of $M = UDU^T$ (where D is diagonal and U is unit triangular) have attracted considerable attention because the computationally expensive scalar square roots of the standard square-root factorization $M = SS^T$ are avoided. From a geometric point of view, the U array expresses estimate errors in terms of a basis set having covariance D, which obtains a more compact derivation of UDU^T processing algorithms than is available in the literature.

Factorizations in the form of $M = A \Sigma A'$, where Σ may have negative diagonal entries, occur in some parallel-processing algorithms and in square-root versions of the Chandrasekhar algorithm. At first glance, the above geometric interpretation appears to imply basis

vectors with negative covariances; however, closer study reveals that the appropriate vectors are individually of positive variance but correlated in such a way that the norms of the A rows are correctly computed via the Σ matrix. Details remain to be investigated, but it is likely that alternative transformations based on the true (positive-definite) covariance of the basis sets may be more numerically stable than "Σ orthogonal" transformations.

d. Realization of Time-Varying Linear Systems (T. Kailath, M. Morf, E. Verriest)

The concept of an operational transfer function was introduced by Kamen. A time-varying multiplier can be interpreted as an operator acting on the space of distributions. We consider a ring T generated by some finite set of such operators and closed under differentiation. A set of linear time-varying differential equations can thus be represented in operator form as $Ay = Bu$, where the elements of the matrices A and B belong to a noncommutative polynomial ring $T[p]$, and p is the differential operator.

Some mathematical properties of $T[p]$ have been derived, particularly a weak-division algorithm (left and right) that leads to the notion of a "greatest common divisor" (left and right) which is not unique because, generally, $T[p]$ is not a Euclidean ring. In addition, an algorithm for a least common multiple (left and right) has been obtained. The existence of a l.c.m. facilitates the "transformation" between LFD and RFD although problems with nonmonicity are as yet unresolved.

System-theoretic applications of the above realizations include the existence of an operational transformation $A^{-1}B$. These canonical realizations also have a natural representation as an L/R-fraction description and an L/R-polynomial form. The well-known Silverman criterion for instantaneous controllability has been presented in a new configuration wherein control is related to the existence of a similarity transformation that brings the realization into controller form. Conditions for such ring realizability are being investigated.

The definition of "mode" has been extended, and the problem of solving a differential equation was observed to be equivalent to the determination of the right factors of a polynomial $T[p]$.

e. Ladder Forms for Least-Squares Estimation (M. Morf, D. Lee, T. Kailath)

Ladder forms are probably the most promising canonical realizations in estimation and system identification because of their low computational complexity, stability "by inspection," and their relationship to such physical properties as reflection or partial-correlation coefficients. In addition, they also appear in scattering and network theory.

We have developed two very useful recursive ladder forms for the exact least-squares linear predictor problem; they are the "prewindowing" ladder in which data values before the known ones are assumed to be zero and the "non-windowing" (or covariance) ladder that works only within the available data. The covariance ladder requires a slight increase in computations, but the undesirable effects caused by the windowing of data are avoided. Both ladder forms are implemented by exponentially weighted error criteria to treat (slowly) time-varying cases, and excellent results have been obtained in such applications as speech modeling and high-resolution spectral estimation.

Work is still in progress to develop a recursive ladder for autoregressive moving average (ARMA) modeling and to implement multichannel (multivariable) ladder forms.

II. DIGITAL SYSTEMS

A. Project 6961. DESCRIPTION LANGUAGES AND DESIGN TOOLS FOR GENERAL-PURPOSE COMPUTER ARCHITECTURES

Principal Investigators: M. J. Flynn, W. M. vanCleemput

Staff: T. Bennett, K. Stevens, E. Slutz, W. Cory, D. Hill, J. Smith, W. Marti, A. von Bechtolsheim

1. Objective

The goals of this study are to develop description languages and other design aids to describe and implement computer architectures and to establish a basis for understanding the computer-design process.

2. Current Status of Work

a. The SPRINT Printed-Circuit Design System (K. Stevens, T. Bennett, W. M. vanCleemput)

The objective of this system is to develop an interactive computer-assisted design of printed-circuit boards. In the SPRINT system, the critical components are manually placed and components such as 14- and 16-pin dual-in-line packages are automatically placed. The interconnection routing module manually routes the critical connections and automatically routes noncritical connections. The current system is limited to two signal layers; however, an extension to multilayer boards is planned.

The input to SPRINT is the Structural Description Language (SDL). This language is also used as input to a logic simulator, a fault test-generation/simulation system, and an automatic logic-diagram generation system.

SPRINT is implemented in MORTRAN and FORTRAN IV on the IBM 370 at SLAC and makes use of the Tektronix 4013 terminal. The SDL compiler is implemented in SPITBOL (a SNOBOL dialect). The output is a plot from which the artwork must be generated manually; however, work is in progress to generate artwork automatically by means of a photoplotter.

b. Computer-Aided Layout of Large-Scale Integrated Circuits (E. Slutz, W. Marti, W. M. vanCleemput)

Although several systems exist for the automated layout of LSI circuitry, none obtains a layout comparable to one designed manually. The objective of this project is to develop and implement a system that uses algorithmic approaches in which certain decisions are the responsibility of the designer. It is expected that this system will reduce design time considerably at no expense of excessive silicon area. The system is now in its initial implementation phase, and the data base and interactive graphics functions are scheduled for completion in 1978.

c. Interactive System for Design Capture (A. von Bechtolsheim, W. M. vanCleemput)

In the current design system, all input is in the form of SDL, the Structural Design Language. Because designers often prefer schematics for their tasks, a system has been implemented that will take as its input a schematic from an interactive graphics terminal and will output an SDL description for further processing by the various design-automation programs. The current version is written in MAINSAIL for the PDP 10 system, and a more portable version, written in PASCAL, is being developed.

d. Implementation of a Digital Design Language (W. Cory, W. M. vanCleemput)

A compiler and simulator system for the Digital Design Language (DDL) is being implemented, based on a compiler-compiler scheme. The system, written in PASCAL, should be reasonably portable and is scheduled to be operational by the second quarter of 1978.

e. Automated Generation of Logic Diagrams (J. A. Smith, W. M. vanCleemput)

A system for the automatic generation of logic diagrams, originally developed at the University of Waterloo, Canada, has been reimplemented and made compatible with the SDL input. This system is written in MORTRAN (a structured FORTRAN preprocessor).

f. Description and Simulation of Computer Architectures (D. Hill, W. M. vanCleemput)

The problem of describing and simulating a computer system at various levels of abstraction is being studied. Currently, no adequate tools exist for simulating a design at multiple levels of abstraction. The current study focuses on the potential use of SIMULA for multilevel simulation of digital systems.

B. Project 7151. COMPUTER ARCHITECTURE

Principal Investigators: E. J. McCluskey, S. S. Owicki
Staff: D. J. Rossetti, F. W. Terman

1. Objective

The objective of this study is to gain new insight into computer architecture and operating systems. We will investigate design methods and programming-language features that aid in producing verifiably correct operating systems.

2. Current Status of Work

A model for designing and describing operating systems and other concurrent programs has been developed. Programming-language features for implementing such systems have been defined and described by formal proof rules. These proof rules have been used to derive verification methods that are now being applied to system programs in the literature.

The second direction of this project is focused on the evaluation of various computer architectures. Two methods that are very helpful in measuring performance--a highly accurate modeling technique and monitoring systems--are being studied.

A set of trace programs has been developed to measure microprocessor performance and to produce unique information concerning the programming ease of various microprocessors. The tracing is highly powerful (it can record interrupts and I/O behavior) and almost transparent (external hardware reduces significantly the amount of perturbation introduced by the tracer).

The investigation of interleaved memory is being extended to the effects of request ordering and to the most efficient ordering. A new model has been developed to evaluate the performance of gracefully degradable multiprocessor systems, based on such measures as availability, processing power, and proportion of time in the degraded mode. The best trade-off between computing power and availability or between hardware vs software fault detection can also be determined.

a. Verifying Concurrent Programs (S. S. Owicki)

Large concurrent programs, such as operating systems or distributed data bases, must be carefully organized if time-dependent errors are to be avoided. We propose a model for structuring such programs. The concurrent system consists of active entities (called processes) and passive entities (called data modules), and all data items must be local to a process or to a data module. The processes are ordinary sequential programs. Data in modules are shared by all processes, but they may access the information by calling procedures defined in the modules. In addition to encapsulation, modules provide protection from time-dependent errors and interprocess synchronization. Data modules can be programmed as shared classes [1].

A system that fits the above model could be verified by directly applying the proof rules described in Ref. 1; however, this would be a very lengthy and tedious task. To make verification feasible, the basic proof rules must be used to obtain more powerful techniques for addressing common situations. For example, we have developed rules for aggregating a set of data modules and processes into a single data module; proofs of the system can then deal with the aggregate as a single entity. A common operating system technique is dynamic allocation of certain resources (such as I/O devices) among a number of processes. During the time that a resource is allocated to a process, it can be treated safely as a local object, thereby greatly simplifying the process proof. We are developing verification techniques for exploiting this simplification and are also attempting to verify a number of published system programs to identify other patterns for which specialized proof techniques would be helpful.

b. Computer-System Measurement and Analysis (D. J. Rossetti)

The objective of this study is to gather and analyze data concerning computer-system performance to improve the efficiency of computer architecture and complex computer-program systems. Our approach is to evaluate analytically and empirically past and future computer architectures. An essential aspect of the work is the collection of valid trace information which can then be applied to specific machine organizations.

Sufficient data are being gathered to characterize the input/output (I/O) and workload environment of large high-performance systems. We are in the process of obtaining complete I/O trace information for use in the architecture of novel storage systems involving new addressing schemes, technologies, and system structures. Four real-time environments are being measured, spanning a variety of operating systems, processors, and I/O configurations.

The study has the following two phases.

- Data collection at the various sites: four large systems are being measured--a scientific research center, an insurance company, a bank, and an aerospace/electronics manufacturer. Data collection involves extensive operating-system modifications and a period (approximately one month) of measurement at each site. This results in the most complete set of such data yet available because it produces a complete trace of file activity over an extended period of time at both macro- and microscopic levels of detail. Currently, three of the four measurements are complete.

- Analysis of the data and their use in workload and performance models: at the end of the measurement phase, we will have obtained a large amount of highly accurate data, especially regarding I/O and storage-system environments. The purpose is to determine the factors that comprise a computing workload, staying as far as possible from installation and configuration dependencies and as close as possible to the "stimuli" exerted by the users (and their programs) on the system. Such data will provide a firm foundation for modeling and performance evaluation of storage systems and new I/O architectures.

c. Memory Interleaving (F. W. Terman)

A series of models of interleaved memory systems has been investigated by trace-driven simulations. The basic model extends the one developed by Burnett and Coffman [2] to the architecture on the IBM 360/370 with its variable-length instructions and operands [3]; it also includes multibyte transfers per memory access. Variations of this model facilitate the study of the effects of channel interference, data-request reordering, and data-queue emptying at interrupts. By a major extension of the simulation model, the effects of more than one processor accessing the same memory can be analyzed.

Memory requests for the simulations are obtained from two sets of instruction-by-instruction trace records. The first set traces the problem state component of typical programs running on the IBM 360/370; the second set traces samples of the total activity of the CPU, including both supervisor and problem states.

The theoretical predictions of Burnett and Coffman [2] for the increase in memory bandwidth caused by interleaving agree with the simulation results obtained for the fetching of instructions. The usefulness of fetching instructions in blocks is limited by the relatively high frequency of branches on the IBM 360/370 machines. Consequently, an active channel has relatively little effect (less than 10 percent degradation) on the fetching of instructions from an interleaved memory.

For the transfer of operands to and from memory, the simulation results reveal only one-half the increase in memory bandwidth predicted by Burnett and Coffman [2], which indicates that data references on the IBM 360/370 are not random as was assumed. The effect of an active channel is again small because of the number of idle modules in a typical memory cycle. A larger degradation (10 to 20 percent) occurs if the data requests are forced to "catch up" with the instruction requests before a successful branch is executed. This is a reasonable restriction because the branch address cannot be calculated with certainty until the values of the general-purpose registers are known. On the other hand, the memory bandwidth can be significantly improved (15 to 30 percent) by filling the data requests out of order.

For high degrees of interleaving, the effective memory bandwidth can be improved considerably by the use of processors; a factor of 1.4 improvement is typical with two processors. Additional improvement (30 to 40 percent) can be obtained by filling data requests out of order; however, the run time of the simulator increases by as much as a factor of 5 when data requests are reordered because of the need to repeatedly scan the queue of data requests. This increase in the run time of the simulator indicates a corresponding increase in the operating time of the memory manager of the actual system.

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III. INTEGRATED CIRCUITS

A. Project 5012. IC PROCESS DESIGN AND COMPUTER MULTILAYER SEMICONDUCTOR DEVICE ANALYSIS

Principal Investigator: R. W. Dutton
Staff: D. B. Estreich

1. Objective

The objective is to study the capabilities to predict and simulate the electrical behavior of multilayer semiconductor devices based on layout and fabrication process modeling.

2. Current Status of Work

This research has focused on distributed multilayer effects on I^2L and CMOS technologies. The multilayer effects in I^2L are used in the design objectives. CMOS multilayer effects can cause potential latch-up hazards and must be avoided.

Results presented recently [1,2] summarize many of the performance and operational limits of I^2L. The intrinsic limits related to sheet resistance and charge storage at high currents can be modeled directly from geometry and technology-dependent effects. The extrinsic limits at low currents depend explicitly on junction capacitance and effective current gain. A method for forming a simplified I^2L model for the extrinsic region is being pursued. The desired attributes involve timing simulation for relatively low-speed control logic functions. The facility to model efficiently I^2L peripheral circuits on high-speed T^2L or EFL chips can achieve a significant saving in simulation time while maintaining the essential multilayer effects of I^2L that relate to the fabrication.

The CMOS latch-up study has focused primarily on test structure considerations for detecting potential hazards. Three key device issues are

- symmetrical path devices (high aspect ratios) where doping and spacing effects dominate; for example, p-well to source dimensions and doping profiles are one critical combination

- field-aided lateral pnp devices where current-gain can be altered substantially by the electric field and basewidth
- accurate determination of sheet resistances such as p-well, guard band, and pinched p-well diffusions

This last item is important in defining conditions for latch-up initiation. There is an auxiliary condition to the unity beta product rule, and analysis indicates that the ratio of p-well to substrate resistivity and available current from the supply are factors in the initiation. The exact nature of this relationship will be investigated.

The principles involved in the CMOS test structure and the measurements of the Stanford test chip will be essential in understanding potential latch-up hazards in new high density technology [3].

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IV. SOLID STATE

A. Project 5111. TRANSPORT PROPERTIES OF $Al_xGa_{1-x}As$, $Al_xGa_{1-x}Sb$ AND $In_xGa_{1-x}As$ SINGLE CRYSTALS

Principal Investigator: G. L. Pearson
Staff: K. Jew

1. Objective

This project is a systematic study of the transport of free carriers in ternary systems. The electronic parameters of interest are free-carrier mobility, resistivity, minority-carrier diffusion length, impurity-activation energy, and trap-energy levels. The distribution coefficients of selected doping impurities as a function of x are significant growth parameters. The results obtained should prove useful in the design of photoluminescent devices, injection lasers, solar cells, infrared detectors, and bulk-effect microwave devices.

2. Current Status of Work

In previous work, (p)$Al_xGa_{1-x}As$:Ge LPE crystals with compositions throughout the $0.0 \leq x \leq 1.0$ range were grown on semi-insulating GaAs:Cr substrates and characterized by Hall measurements. The results obtained from these measurements were generally consistent except for crystals of high aluminum content $(x > 0.6)$ in which the data were scattered. This behavior is assumed to be caused by the difficulty in doping $Al_xGa_{1-x}As$ layers with $x > 0.6$ because the carrier concentration decreases exponentially with increasing x. During the past reporting period, (p)$Al_xGa_{1-x}As$:Ge was further investigated by repeating the Hall measurements on a separate set of crystals grown with higher dopant concentrations.

Before each growth run, the Ga melt was baked out at 800°C for 12 hours under flowing H_2. The p-type epitaxial layers were prepared from Ga melts containing Ge, a GaAs source, and Al. The dopant concentration in the melt was increased from 0.5 to 2.0 atomic percent Ge to obtain higher carrier concentrations in the grown layer. The crystals were grown in the temperature interval of 800° to 785°C and at a cooling rate of 0.2°C/min.

Hall measurements of the (p)$Al_xGa_{1-x}As$:Ge crystals were based on the Van der Pauw technique. Carrier concentration, mobility, and resistivity were measured in the temperature interval 77° to 300°K. The results obtained agree with previously reported data.

The hole concentration at 300°K decreases as aluminum content is increased. In these crystals grown from melts doped with 2 percent Ge, the hole concentration has an exponential dependence on aluminum content x as $p(x) = 2.38 \times 10^{18} \exp(-4.73x)\ cm^{-3}$.

The variation of carrier concentration with temperature was used to determine the thermal activation energy of the Ge acceptor. The activation energies obtained from the current set of crystals is consistent with $E_A = 175x + 10$ MeV. For samples of high aluminum content, the earlier values for E_A were scattered off this line; however, the present measurements used crystals grown with higher dopant concentrations, and the results for E_A vs x are more consistent.

The measured hole mobilities at 300°K are in agreement with $\mu_p(x) = 27.8\ (0.48 + 0.31x)^{-5/2}\ cm^2$ N-sec. The hole mobility decreases as aluminum content x is increased because of the variation of the hole effective mass in the $Al_xGa_{1-x}As$ system.

Current study is directed toward the growth of (n)$Al_xGa_{1-x}As$: Sn which will be characterized by Van der Pauw, photoluminescence, I-V, C-V, and scanning electron-microscope techniques.

B. Project 5244. STUDIES OF HIGH-TRANSITION SUPERCONDUCTORS SUCH AS V_3Si AND Nb_3Sn AND DEPTH PROFILING OF Nb_3Sb JOSEPHSON JUNCTIONS

Principal Investigator: W. E. Spicer
Staff: I. Lindau, J. Miller

1. Objective

The purpose of this project is to explore the electronic structures of type-II (hard) superconducting alloys, particularly Nb_3Sn, to determine such parameters as valence bandwidth which is important to the theoretical models of superconductors. Emphasis is directed toward the preparation of atomically clean Nb surfaces, evaporation of Sn as an adlayer, and annealing to form Nb_2Sn.

2. Current Status of Work

We have successfully prepared a clean Nb surface and have admitted controlled amounts of oxygen to the system to observe (via UPS) the initial stages of oxidation on the Nb surface. The results indicated that the photoemission spectra at 21.2 was not inconsistent with the bulk density of states calculated by Ho, Louie, Chelikowsky, and Cohen† and led to the postulation of a model for the formation of oxides on the clean Nb surface. At small exposures of oxygen, a peak is observed at 6.5 eV from E_f which is related to a chemisorption stage. At higher exposures, a second peak appears at 7.3 eV from E_f which is associated with a surface NbO_x, where $x = z$ is a likely candidate. At exposures up to saturation, a new peak grows at 8.2 eV along with the 7.3 eV peak. Because the resulting spectra is similar to the air-oxidized Nb which is known to consist mainly of Nb_2O_5, the final phase is related to the formation of Nb_2O_5 at the surface. This research was presented in a paper at the Physics of Transition Metals Conference.‡

Recent work has focused on the preparation and construction of equipment for new experiments. A more grazing-incidence monochrometer is being designed and constructed to improve the utility and resolution of the He resonance lamp. When this device is completed, shallow core levels of many materials and adsorbates will be accessible so that chemical shifts can be measured. From these chemical-shift data and enhanced high-resolution valence-band data, significant information can be obtained concerning the chemical state of the surface. They can also be used to finger print different gases chemisorbed on the metal surface. The equipment should be completed during the next reporting period, and work should begin on the formation and study of Nb_3Sn and on the use of sputter Auger techniques to study Josephson junctions.

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†Phys. Rev., B-15, 1977, p. 1755.

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V. RADIOSCIENCE

A. Project 3606. REAL TIME DIGITAL SIGNAL PROCESSING: ALGORITHMS AND SYSTEM ARCHITECTURE

Principal Investigator: A. M. Peterson
Staff: S. Narayan, M. J. Narasimha, A. I. Abu-el-haija

1. Objective

The objective of this research is the development of algorithms and digital system designs to efficiently and economically implement real-time digital signal-processing hardware. The proposed research is based on the belief that many signal-processing functions in communication, radar, sonar, and other systems, now implemented by analog circuits, can be more reliably and economically implemented by digital hardware using microprocessors and existing MSI/LSI or new device designs resulting from the research.

2. Current Status of Work

During the past two years, the feasibility and utility of very large digital-array signal-processing systems have been investigated. This work was initiated by a request from NASA Ames Research Center for a million-channel spectrum analyzer; it was then extended to other applications, such as processors for synthetic aperture radar (SAR) azimuth beam forming and for processing wideband signals associated with planetary bistatic radar and radio-wave occultation experiments. This same processor array can also do two-dimensional processing of radar images required as a part of an ONR-supported oceanographic research project aimed at sensing ocean-surface characteristics by synthetic aperture radar. These images are now obtained from aircraft but will soon be obtained by the SEASAT-A spacecraft. This processor array would be able to perform 1000-1000 element two-dimensional spectral transforms in a fraction of a second. As a near-term application, our research could provide a real-time digital image-forming system for the SEASAT-A synthetic radar.

In the existing system design for a million-channel digital spectrum analyzer, digital bandpass filtering transforms a wideband input signal from a single input channel into many narrower bandwidth output channels. For example, a single 2^{20} Hz $\simeq$ 1 MHz channel may be split into 128 channels, each with a $(2^{20}/2^{7} = 2^{13})$ = 8192 Hz bandwidth. The outputs of this channel-splitting digital bandpass-filter bank can be processed in 2^{7} = 128 microprocessor-based FFT computers, each producing 2^{13} = 8192 output channels with a 1 Hz bandwidth. The bandpass filters that precede the FFT processors reject interference ($\geq$60 dB) in all channels except the one occupied by the interfering signal. After passing through the 128-channel filter band, each channel is independent of the others and requires identical FFT processing to obtain the final bandwidth. The bandpass-filter bank that precedes the parallel-processor array can be constructed in a modular form. One structure that has been studied would have a single input processor with 2^{4} = 16 output bands; each of the 16 output channels would be followed by processors which, in turn, provide eight output channels. The complete system would include 128 microprocessors, each computing an 8K transform by performing identical operations at every clock cycle but on different input data corresponding to the outputs of the 128 bandpass filters. This system design is capable of operating over a wide range of input bandwidths up to $\approx$6 MHz.

Recent work has demonstrated that system performance can be enhanced by using DFT algorithms [1], and this work has been extended at Stanford [2] and by Kolba and Parks [3] through "prime factor" algorithms that are much faster than conventional FFT implementations based on powers of two. This approach is especially applicable to the bandpass filters required in the million-channel analyzer. In particular, a prime-factor implementation of a 120-point DFT based on 8-, 5-, and 3-point DFTs requires only one-third as many multiples as a 128-point base-2 FFT. Prime-factor algorithms should also facilitate the convolution operations necessary in SAR image formation discussed below.

Because this digital spectrum analyzer is modular, only three of the modules (printed circuit boards) need be built to test the performance of the final system. These modules are one of the 128-output FFT

processors, one of the 16 base-eight FFT processors, and one base-16 processor (or base $3 \times 5 = 15$ if the prime-factor algorithm is used). These three building blocks provide the basis for a wideband "scanning" digital spectrum analyzer with impressive capabilities. When the remaining modules are duplicated, the full parallel analyzer or any portion of it can be implemented rapidly.

Azimuth processing of the SEASAT-A SAR data requires beam-forming computation and various doppler and range-walk corrections on the 4000-range intervals that comprise a 100 km range swath. The above processor array (128 processors) would do the necessary convolution processing, and a single unit could handle an 800 m range interval. All necessary azimuth processing on 32 range cells can be performed in a single processor in real time. As a result, the full 100 km range swath can be processed in real time by 120 processors. Processing of approximately one-half second of the 1600 pulse/sec data is required to produce the desired 25 m azimuth resolution.

The range compression of the SEASAT SAR chirped signal can be done digitally in a special processor that precedes the multiprocessor beam-forming system. This new preprocessor would make use of the fast convolution techniques [3] or the special chirp-filter design developed by Narasimha [4].

The modular design of the proposed system plus LSI results in impressive performance at modest cost. The proposed design is based on the 2900 family of bipolar microprocessors (4-bit slice architecture). The recently available parallel multipliers (Monolithic Memories 6-7558 and TRW MPY 16) and serial parallel multipliers (AMD 25L514) also improve performance. The memory for data storage in the 128-output processing is the principal cost of the system.

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B. Project 4214. INVESTIGATION OF UNDERSEA COMMUNICATION WITH ULF/ELF ELECTROMAGNETIC WAVES

Principal Investigator: O. G. Villard, Jr.
Staff: A. C. Fraser-Smith, D. M. Bubenik, A. Ho

1. Objective

The objective of this project is to investigate the propagation of ULF/ELF electromagnetic waves in the sea (frequencies less than 300 Hz) from undersea harmonic dipole sources, considering the effects caused by the presence of the ocean floor. This is an extension of earlier work [1,2,3] concerning only an ocean of effectively infinite depth.

2. Current Status of Work

This project consists of (1) derivations of the mathematical expressions for the fields of harmonic dipole sources located in an ocean of finite depth, (2) evaluation of these expressions, and (3) analysis of the results. These stages have been completed, and a paper entitled "ULF/ELF Electromagnetic Fields Generated in a Sea of Finite Depth by a Submerged Vertically Directed Harmonic Magnetic Dipole" by D. M. Bubenik and A. C. Fraser-Smith is ready for publication.

ABSTRACT

In this paper, we compute the undersea quasi-static electromagnetic fields of a submerged vertically directed harmonic magnetic dipole (VMD), taking into account the presence of a sea floor, for evaluating the relative importance of the modes of propagation of the fields at frequencies in the ULF/lower ELF bands (frequencies less than 300 Hz). The source and the receiver are located equidistant from the surface and floor of a sea one skin depth (δ), and the horizontal separation (r)

between them is varied in the range 0.1 δ and 100 δ. When the horizontal separation between the receiver and the VMD source is less than approximately eight skin depths, each field component behaves as though the source were in a sea of wholly infinite extent. At larger separations, the ratio of the actual field to the "infinite extent" (or direct) field amplitudes increases rapidly and reaches a value exceeding 10^{36} at a separation of 100 skin depths, indicating that the fields at such distances have not propagated directly through the sea water. Analysis of the propagation modes reveals that the chief contribution at large separations ($r/\delta > 20$) is the surface mode, and the field amplitudes in this asymptotic regime are independent of sea floor conductivity. At closer ranges ($r/\delta < 10$) where the direct contribution dominates, the surface and sea-floor modes are of equal importance. Between these limiting cases is a transitional regime where the first-order sea-floor contribution is a significant, if not dominant, mode. The changeover between the transitional and the asymptotic regimes moves outward from the source as the sea floor conductivity decreases, and the field components in the asymptotic regime are characteristic of a quadrupole or higher order source.

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C. Project 4504. TROPOSPHERIC RADIO PROPAGATION

Principal Investigator: A. T. Waterman
Staff: R. D. Fleming, T. Torvaldson, S. DeLateur

1. Objective

The objective of this research is to investigate atmospheric parameters and phenomena in the lower troposphere based on radio propagation in the S-band. The goals are to

- measure wind velocity in the common volume of a transhorizon troposcatter propagation path by means of doppler techniques

- probe the structure of winds and turbulence in the lower troposphere under various conditions of atmospheric stability and instability

The plan of operation involves the simultaneous reception of 3 GHz CW signals from a transmitter located 100 miles away (beyond line-of-sight). Each of two narrow beams are aimed on either side of the great-circle bearing toward the transmitter by small amounts (1° or less). If a wind component is transverse to the path in the region of the common volume, it is anticipated that the signal received on one beam will be doppler shifted to higher frequencies and that the signal on the other will be shifted to lower frequencies. The magnitude of the doppler difference should be proportional to transverse-wind velocity. The two beams will be formed during data reduction because the receiving antenna is a sampling array that measures and stores on digital tape the amplitudes and phases of the signal received on 12 individual antennas. To obtain high azimuthal resolution, the antennas are arranged in a horizontal linear array.

2. Current Status of Work

Preliminary to taking data on the transhorizon path, the system was checked out on a line-of-sight path. The transmitter was operated from six locations 15 km from the receiving array. These six locations include two in line with the great-circle bearing in the direction of the eventual transhorizon location, two 1° to the right, and two 1° to the left. For each of the three pairs, the separation was five minutes of arc. This test serves to verify the accuracy of the angle-of-arrival determination, the stability of the phase measurements, the overall operation of the system, and the procedures to be followed in the transhorizon experiment.

In preparation for the data-analysis procedures, some exploratory computational work has been done on past data (which used vertical angle-of-arrival rather than azimuthal) and also on the data of these line-of-sight tests. This work has included some experimentation with the maximum-entropy method of analysis as applied spatially to antenna arrays.

VI. PLASMA PHYSICS AND QUANTUM ELECTRONICS

A. Project 1337. GENERATION OF INTENSE MICROWAVE RADIATION

Principal Investigator: F. W. Crawford
Staff: S. E. Rosenthal

1. Objective

The aim of this project is to design and construct a high-power magnetron capable of producing ~1 GW ~1 μs (~1 kJ energy) pulses at ≈3 GHz.

2. Current Status of Work

Work is continuing on scaling up in power the high-power long-anode magnetron tube of Boot et al [1] to the relativistic electron energy range. The anode block has been designed, a prototype constructed, and the normal modes identified by standard cold testing techniques [2]. Work is currently directed towards design of the coupling-out structure and the indirectly-heated cathode.

The order for the specially-constructed high-voltage pulse generator and associated power supply has been placed, after detailed considerations of bids by three different manufacturers. Its cost has been covered primarily by a grant from the Physics Division of the NSF and a matching grant from the Stanford University School of Engineering. It is anticipated that the supply will be delivered early in 1978.

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B. Ginzton Laboratory. TWO-PHOTON RESONANTLY PUMPED IR UP-CONVERTERS

Principal Investigators: S. E. Harris, J. F. Young
Staff: J. H. Newton

1. Objective

The goals of this project are the development and extension of efficient IR up-conversion techniques in metal vapors, particularly image up-conversion.

2. Current Status of Work

The up-conversion of 2.94 μm IR images to 4556 Å has been demonstrated in Cs vapor. A power efficiency of 20 percent, with over 10,000 resolvable spots, was obtained using a pump power of 200 kW focused on an area of 1.1 cm^2. The Cs cell had an active length of 0.3 cm and was operated at a density of 2.0×10^{17}/cc. Images of a resolution test target indicated a resolution of better than 12 lines/mm; this is a factor of 2.5 of the diffraction limit of the optical system used. The pumping laser, Nd:lanthanum-berylate, has a natural two-photon coincidence with the $6s^2S$ to $7s^2S$ transition, resulting in a simple practical system with a number of potential applications.

During the last reporting period, experiments were performed to determine the limiting values of up-conversion efficiency as functions of pump-power density and Cs density to optimize the system. The power-density experiment was completed and revealed a higher allowed density than was calculated. The Cs density experiment was only partially completed because of a problem with the Cs cell. Further calculations were made on an extension of this device, called a spectral up-converter.

The relationship between efficiency $\mathcal{E}$ and resolvable spots R and the operating parameters are

$$\mathcal{E} \propto \frac{N^2 L^2 P^2}{A^2} \qquad R \propto \frac{A}{L} \qquad \mathcal{E} \propto \frac{N^2 L P^2}{A}$$

where

N = Cs density

L = cell length

A = area of pump beam

P = pump power

To maximize $\delta \cdot R$, A can be made as small as possible by focusing tightly; however, P/A is limited by two-photon absorption of the pump and saturation of the two-photon transition. The calculation of two-photon transition probabilities had indicated that complete saturation should occur at a power density of 500 kW/cm^2, but measurements revealed that the IR up-conversion efficiency was still increasing quadratically at densities of 500 kW/cm^2 and increasing near the 3/2's power at 2 MW/cm^2. The increase was still linear at 3.5 MW/cm^2. Because the tripling of the pump ($\omega_s = 3\omega_p$) and the infrared up-conversion process ($\omega_s = 2\omega_p + \omega_{IR}$) have the same dependence on two-photon absorption, one can measure the tripling efficiency vs pump-power density and determine the up-conversion efficiency behavior. The exponent of the pump power in up-conversion will be one less than that for the tripling process. This method is experimentally easier to perform. Third harmonic power vs pump-power density is plotted in Fig. 1.

At some Cs density, self-broadening of the $6s^2S - 7s^2S$ two-photon transition surpasses the doppler linewidth. Because efficiency is inversely proportional to linewidth and the self-broadened linewidth is proportional to Cs density N, efficiency at high densities will only increase linearly with N. Two other factors related to increasing N limit efficiency. First, absorption of the sum frequency increases as the self-broadened linewidth of the $6s^2S - 7p^2P^0$ transition increases and, secondly, the Cs_2 molecule density rises with Cs density and causes absorption at the pump frequency. We have not yet been able to make these measurements at sufficiently high densities to observe such limits. A cold spot developed in the cell and, even with maximum heating of the side arm, high enough Cs densities cannot be achieved to run the experiment successfully. The cell is being modified to correct the problem.

Further investigation of the spectral up-converter has yielded some interesting results. This process has the same two-photon absorption limitations as the IR up-converter and can be pumped with higher

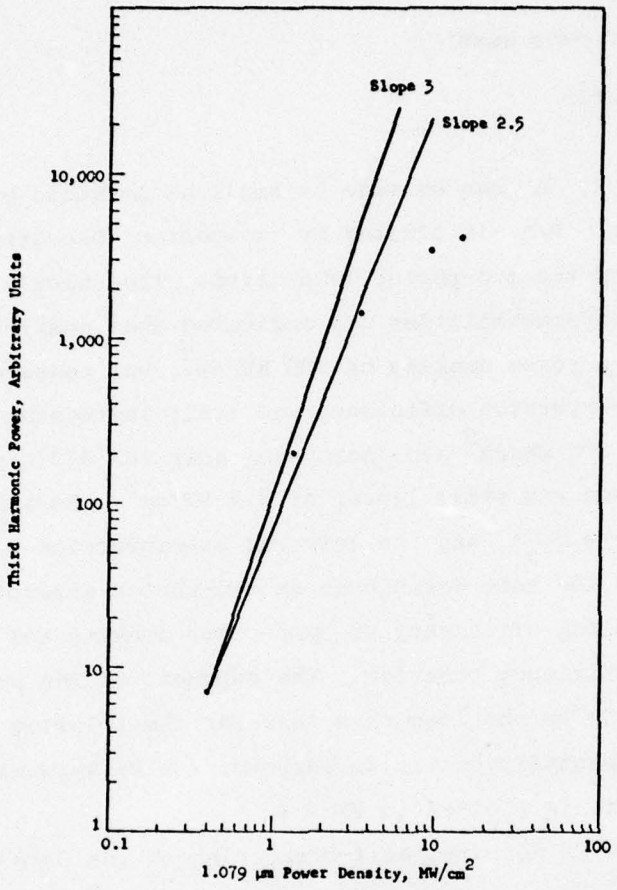

Fig. 1. PUMP POWER DENSITY SATURATION.

pump-power densities than previously calculated. It is possible to angle phasematch the process over many coherence lengths and over a rather large bandwidth of the IR by splitting the pump beam into two parts and recombining them at the up-converter at the appropriate angle. Using a power density of 1 MW/cm^2, a Cs density of $10^{18}/cc$, and a cell length of 0.3 cm, a photon efficiency of greater than 14 percent can be achieved over an IR bandwidth of 1400 cm^{-1}. This device would have valuable applications for recording broadband IR spectra, particularly when fast time resolution is required.

Appendix A

OUTSIDE PUBLICATIONS

1. Papers Presented at Meetings

Information Systems

Cot, N. and J. Gill, "Bounds on the Cost of Optimal Uniquely Decipherable Codes," IEEE Intl. Symp. on Information Theory, Ithaca, New York, 10-14 Oct 1977.

Cover, T. and C. Leung, "A Rate Region for the Multiple-Access Channel with Feedback," ICC Intl. Conf. on Communications, Chicago, Ill., Jun 1977.

Cover, T., "Multi-Way Channels and Feedback," Tenth European Meeting of Statisticians, Leuven, Belgium, Aug 1977.

Cover, T., "Multiple Access Feedback Channels," IEEE Intl. Symp. on Information Theory, Ithaca, New York, Oct 1977.

Dunham, J. and R. M. Gray, "Joint Source-Channel Time-Invariant Trellis Encoding," IEEE Intl. Symp. on Information Theory, Ithaca, New York, Oct 1977.

Friedlander, B., T. Kailath, and M. Morf, "A Modified 'Displacement Rank' and Some Applications," Proc. IEEE Conf. on Decision and Control, New Orleans, Dec 1977, pp. 958-961.

Friedlander, B., G. Verghese, and T. Kailath, "Scattering Theory and Linear Least Squares Estimation, Pt. III: The Estimates," Proc. IEEE Conf. on Decision and Control, New Orleans, Dec 1977, pp. 591-597.

Gray, R. M. and D. S. Ornstein, "Block Coding for Discrete Stationary d-Continuous Noisy Channels," IEEE Intl. Symp. on Information Theory, Ithaca, New York, Oct 1977.

Hellman, M. and S. K. Leung-Yan-Cheong, "Gaussian Wiretap Channel," IEEE Intl. Symp. on Information Theory, Ithaca, New York, 10-14 Oct 1977.

Kung, S-Y., T. Kailath, and M. Morf, "Fast and Stable Algorithms for the Minimal Design Problems," IFAC, Canada, 4-8 Jul 1977.

Lévy, B., S-Y. Kung, M. Morf, and T. Kailath, "A Unification of System Equivalence Definitions," Proc. IEEE Conf. on Decision and Control, New Orleans, Dec 1977, pp. 795-800.

Lévy, B., M. Morf, and S-Y. Kung, "New Results in 2-D Systems Theory, Pt. III: Recursive Realization and Estimation Algorithms for 2-D Systems," 20th Midwest Symposium on Circuits and Systems, Lubbock, Texas, Aug 1977.

Linde, Y. and R. M. Gray, "The Simulation Problem," Intl. Symp. on Information Theory, Ithaca, New York, Oct 1977.

Morf, M., B. Lévy, and T. Kailath, "Square-Root Algorithms for the Continuous-Time Linear Least Squares Estimation Problem," Proc. IEEE Conf. on Decision and Control, New Orleans, Dec 1977, pp. 944-947.

Morf, M., A. Vieira, D. Lee, and T. Kailath, "Recursive Multichannel Maximum Entropy Method," JACC, San Francisco, Jun 1977, pp. 113-117.

Verghese, G. and T. Kailath, "Fixing the State-Feedback Gain by Choice of Closed-Loop Eigensystem," Proc. IEEE Conf. on Decision and Control, New Orleans, Dec 1977, pp. 1245-1248.

Digital Systems

Owicki, S. S., "Verifying Concurrent Programs with Shared Data Classes," Working Conf. on Formal Description of Programming Concepts, New Brunswick, Canada, 31 Jul-5 Aug 1977.

vanCleemput, W. M., "An Algorithm for Testing the Planarity of Partially Oriented Graphs," Record of the Midwest Symp. on Circuits and Systems, Lubbock, Texas, Aug 1977.

vanCleemput, W. M., T. C. Bennett, J. A. Hupp, and K. R. Stevens, "SPRINT: An Interactive System for Printed Circuit Board Design," Proc. IEEE Computer Soc. Intl. Computer Software and Applications Conf., Chicago, Nov 1977.

vanCleemput, W. M. and E. A. Slutz, "Initial Design Considerations for a Hierarchical IC Layout System," Proc. Asilomar Conf. on Circuits, Systems, and Computers, Pacific Grove, Calif., Nov 1977.

Solid State

Miller, J., I. Lindau, and W. E. Spicer, "The Electronic Structure and Oxidation of Niobium," Toronto, Canada, Aug 1977.

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Abu-el-haija, A. I., K. Shenoi, and A. M. Peterson, "A Structure Suitable for Implementing Digital Filters with Poles near $z = +1$," Proc. Natl. Telecom. Conf., 1978.

Abu-el-haija, A. I., K. Shenoi, and A. M. Peterson, "Recursive Filters Implemented by Digital Incremental Computers," Proc. 20th Midwest Symp. on Circuits and Systems, Aug 1977, pp. 892-928.

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Information Systems

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Cover, T. and J. van Campenhout, "On the Possible Orderings in the Measurement Selection Problem," IEEE Trans. on Systems, Man, and Cybernetics, SMC-7, Sep 1977, pp. 657-661.

Gill, J., "Computational Complexity of Probabilistic Turing Machines," SIAM J. on Computing, 6, Dec 1977, pp. 675-696.

Gray, R. M. and L. D. Davisson, "Second Order Moments and Prediction for Doubly Reflected Symmetric Independent Increment Processes," SIAM J. of Applied Math., 33, Dec 1977, pp. 559-567.

Johnson, C. R., Jr. and M. G. Larimore, "Comments on and Additions to 'An Adaptive Recursive LMS Filter'," Proc. IEEE, Sep 1977, pp. 1399-1401.

Kailath, T. (ed.), "Linear Least-Squares Estimation," Benchmark Papers in Electrical Engineering and Computer Science, Stroudsburg, Dowden, Hutchinson & Ross, Inc., 1977.

Kung, S-Y., B. Lévy, M. Morf, and T. Kailath, "New Results in 2-D Systems Theory, Pt. II: 2-D State-Space Models--Realization and the Notions of Controllability, Observability, and Minimality," Proc. IEEE, 65, Jun 1977, pp. 945-961.

Ljung, L. and T. Kailath, "Efficient Change of Initial Conditions, Dual Chandrasekhar Equations, and Some Applications," IEEE Trans. on Automatic Control, AC-22, Jun 1977, pp. 443-447.

Morf, M., B. Dickinson, T. Kailath, and A. Vieira, "Efficient Solution of Covariance Equations for Linear Prediction," IEEE Trans. on Acoustics, Speech, and Signal Processing, ASSP-25, Oct 1977, pp. 429-434.

Morf, M. and T. Kailath, "Recent Results in Least-Squares Estimation Theory," Annals of Economic and Social Measurement, 6, 1977, pp. 261-274.

Morf, M., B. Lévy, and S-Y. Kung, "New Results on 2-D Systems Theory, Pt. I: 2-D Polynomial Matrices, Factorization, and Coprimeness," Proc. IEEE, 65, Jun 1977, pp. 861-872.

Pursley, M. B. and R. M. Gray, "Source Coding Theorems for Stationary, Measurable, Continuous Time Stochastic Processes," Ann. Prob., 5, Dec 1977, pp. 966-986.

Treichler, J. R., "The Spectral Line Enhancer--The Concept, an Implementation, and an Application," Ph.D. Dissertation, Department of Electrical Engineering, Stanford University, Stanford, Calif., Jun 1977.

Widrow, B. and J. M. McCool, "Comments on 'An Adaptive Recursive LMS Filter'," Proc. IEEE, Sep 1977, pp. 1402-1404.

Integrated Circuits

Estreich, D. B. and R. W. Dutton, "Modeling Integrated Injection Logic (I^2L) Performance and Operational Limits," IEEE J. Solid State Circuits, SC-12, Oct 1977, pp. 450-456.

Estreich, D. B. and R. W. Dutton, "An Integrated Injection Logic (I^2L) Macromodel," WESCON 1977, Sep 1977, pp. 1-9.

Solid State

Garner, C. M., Y. D. Shen, J. S. Kim, G. L. Pearson, W. E. Spicer, J. S. Harris, and D. D. Edwall, "Auger Profiling of 'Abrupt' LPE $Al_xGa_{1-x}As$ Heterojunctions," J. Appl. Phys., 48, Jul 1977, p. 3147.

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Radioscience

Abu-el-haija, A. I., K. Shenoi, and A. M. Peterson, "A Structure Suitable for Implementing Digital Filters with Poles near $z = +1$," Proc. Natl. Telecom. Conf., 1978.

Narasimha, M. J., K. Shenoi, and A. M. Peterson, "The Arcsine Transform and Its Application in Digital Signal Processing," Conf. Record IEEE Intl. Conf. on Acoustics, Speech, and Signal Processing, May 1977.

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Information Systems

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Cover, T. and A. El Gamal, "Capacity Theorems for the Relay Channel," IEEE Trans. on Information Theory.

Cover, T. and R. King, "A Convergent Gambling Estimate of the Entropy of English," IEEE Trans. on Information Theory.

Cover, T. and C. Leung, "Some Inequalities between Shannon Entropy and Kilmogorov Chaitin and Extensions Complexities," IEEE Trans. on Information Theory.

Friedlander, B., T. Kailath, M. Morf, and L. Ljung, "Extended Levinson and Chandrasekhar Equations for General Discrete-Time Linear Estimation Problems," IEEE Trans. on Automatic Control.

Kailath, T., B. Lévy, L. Ljung, and M. Morf, "Fast Time-Invariant Implementations of Gaussian Signal Detectors," IEEE Trans. on Information Theory.

Kailath, T., A. Vieira, and M. Morf, "Inverses of Toeplitz Operators, Innovations, and Orthogonal Polynomials," SIAM Review, 20, Jan 1978.

Leung-Yan-Cheong, S. K. and M. E. Hellman, "The Gaussian Wire-Tap Channel," IEEE Trans. on Information Theory.

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Morf, M., A. Vieira, D. Lee, and T. Kailath, "Recursive Multichannel Maximum Entropy Spectral Estimation," IEEE Trans. on Geoscience and Electronics.

Digital Systems

vanCleemput, W. M., "On the Planarity of Hypergraphs," Proc. IEEE.

Solid State

Garner, C. M., Y. D. Shen, C. Y. Su, G. L. Pearson, and W. E. Spicer, "Auger Profiling Studies of LPE (n)$Al_xGa_{1-x}As$-(n)GaAs Heterojunctions and the Absence of Rectification," J. Vac. Sci. Technol.

Houng, Y. M. and G. L. Pearson, "Deep Trapping Effects at the GaAs-GaAs:Cr Interface in GaAs FET Structures," J. Appl. Phys.

Kocot, K. and G. L. Pearson, "Experimental Verification of Cr^{2+} Models of Photoluminescent Transitions in GaAs:Cr and $Al_xGa_{1-x}As$:Cr Single Crystals," Solid State Comm.

Miller, J., I. Lindau, and W. E. Spicer, "The Electronic Structure of Clean and Oxidized Niobium," International Conference on Physics of Transition Metals, in press.

Radioscience

Narasimha, M. J., "Design and Applications of Uniform Digital Band-pass Filter Banks," IEEE Trans. on Circuits and Systems.

Narasimha, M. J. and A. M. Peterson, "On the Computation of the Discrete Cosine Transform," IEEE Trans. on Communications.

Shenoi, K., M. J. Narasimha, and A. M. Peterson, "On the Design of Recursive Digital Low Pass Filters," IEEE Trans. on Circuits and Systems.

Appendix B

ABSTRACTS OF REPORTS PUBLISHED DURING THIS PERIOD

This appendix is a compilation of abstracts of reports issued by the Stanford Electronics Laboratories (SEL).

WHISTLER PROPAGATION IN
A DISTORTED QUIET-TIME
MODEL MAGNETOSPHERE
by Nathan Thomas Seely, III

NSFASS Grant ATM75-07707
and Grant ATM75-15852
NSFDPP Grant DPP-74-0493
TR No. 3472-1
August 1977

ABSTRACT

The time delay versus frequency of ground received whistlers provides valuable information on electron density and convection patterns throughout the magnetosphere. In the past, the magnetospheric environment in which whistlers propagate has most often been modeled by using a dipole magnetic field and field line plasma density models with constant ion-electron temperatures. While the dipole magnetic model is a good first approximation for many whistler studies of the magnetospheric equatorial region out to ~6-7 earth radii (R_E), the region beyond this distance requires a magnetic model that reflects the significant departures from a dipole that exist due to the interaction of the geomagnetic field with the solar wind and currents within the magnetosphere. Some current and future experiments require an improved magnetic model to better relate the equatorial positions of field lines to their projections in the ionosphere. Also, the effect on whistler studies of the significant ionosphere-magnetosphere plasma temperature differences observed along field lines has not been explored.

This research compares whistler analyses based on the traditional models with analyses based on 1) a hybrid quiet-time magnetospheric magnetic field model that combines an internal field model with a model of the average quiet-time contributions to the internal field of the ring, tail, and magnetopause current systems, and 2) a model of the plasma density along field lines that includes significant plasma temperature gradients. The major conclusions of this comparison are:

1) Results of whistler studies of the equatorial magnetosphere based on the quiet-time hybrid magnetic field model are not significantly different from those based on a dipole magnetic field model in the region out to ~6-7 R_E.

2) Beyond 6-7 R_E, whistler measurements of equatorial path positions, electron densities, and electric fields based on a dipole model are subject to significant error. In particular, a) inferred values of geocentric equatorial positions of whistler propagation paths can differ

by 0.5 to 1 R_E, b) calculated equatorial electron densities can differ by 50%, and c) calculations of magnetospheric electric fields using a dipole model can be a factor of 2 or more smaller than those based on the hybrid model.

3) The hybrid magnetic model should be used, instead of the dipole model, in correlative studies in which comparisons of ground or ionospheric measurements with magnetospheric measurements are desired. Use of the dipole or internal magnetic model can lead to inconsistencies between the ionospheric exit positions of whistler mode signals, as found by direction finding techniques, and the projection to the ionosphere of their magnetospheric equatorial positions, as found by whistler analysis.

4) Values of whistler deduced equatorial quantities are not significantly affected by temperature profiles in which the largest temperature gradients occur near the 1000 km altitude base of the field line.

5) Values of whistler-deduced equatorial quantities are significantly affected by temperature profiles with rapid variation of the temperature near the equator. Near 4 R_E, if a constant-temperature plasma model is used, overestimates of equatorial electron density by 50% or more and underestimates of equatorial path position by 2.5% (0.1 R_E) or more can result from temperature gradients $\gtrsim 0.4°K/km$ near the equator. These effects can be comparable to or larger than those resulting from hybrid-dipole magnetic model differences.

6) Whistler-deduced electron concentrations at 1000 km altitude can be increased 2 to 4 fold, depending on the nature of the temperature gradient at that altitude, thereby giving better agreement with certain low altitude satellite data on electron concentration.

NON-LINEAR GYRORESONANT INTERACTIONS OF ENERGETIC PARTICLES AND COHERENT VLF WAVES IN THE MAGNETOSPHERE

by Umran Savas Inan

NASA NGL 05-020-008
ONR Nonr N00014-75-C-1095
and Nonr N00014-76-C-0689
TR No. 3414-3
August 1977

ABSTRACT

The study of wave particle interactions in the earth's magnetosphere has advanced markedly in the last decade. Understanding of these interactions is important because of their possible impact on the ionosphere in general and VLF and ULF communications in particular, their control of the radiation belt particles and the role played by the waves in diagnostics of the magnetosphere. One important class of wave particle interactions is the gyroresonant interaction of coherent VLF whistler mode waves and energetic particles. The waves involved can be natural whistlers or discrete emissions or signals injected into the magnetosphere from VLF ground transmitters, such as the Stanford University transmitter at Siple, Antarctica, and large scale power grids. These coherent waves interact in the cyclotron-resonance mode with the energetic particles trapped in the radiation belts. As a result the waves grow or decay in amplitude and the particles are perturbed in pitch angle and energy. The perturbations in pitch angle are of special importance in that they result in precipitation of particles into the ionosphere. Until recently this effect has only been studied using linear theory and analytical techniques. In the present work, a computer simulation study of this interaction is made with special emphasis on computing the wave's effect on the particles. With this approach it is possible to obtain a full nonlinear solution of the equations of motion in an inhomogeneous medium. The nonlinear results are compared with those of the linear theory and a convenient criterion is presented for determining when a complete nonlinear solution is required. It is found, for example, that in the case of equatorial scattering by a 5 kHz CW pulse near $L = 4$ linear theory begins to break down when the wave amplitude exceeds 3 mγ. We represent a full distribution of energetic particles by 40-50,000 test particles, distributed appropriately in phase space. By computing the complete trajectories of all these particles the perturbation of the full distribution is estimated. The wave induced precipitated flux is computed and it is shown that significant particle fluxes (order of 10^{-1} ergs/cm^2-sec) can be precipitated into the

atmosphere by waves of moderate intensity (order of 10 mγ). These fluxes produce significant perturbations in the nighttime ionosphere. Both the incoming fluxes and the ionospheric perturbations appear to be measurable by presently available instruments.

A FEASIBILITY STUDY
OF A POCKET-SIZED GAS
CHROMATOGRAPHIC AIR ANALYZER
by Stephen C. Terry
and John H. Jerman

Contract NIOSH-210-76-0140
Final Contract Report
July 1977

ABSTRACT

The feasibility of producing a pocket-sized air contaminant monitor based upon a miniature gas chromatograph and an integrated microcomputer has been demonstrated and a practical design for the instrument is presented. This pocket-sized instrument is intended to be used as a personal exposure monitor which is unobtrusively carried by an industrial worker throughout the day. The proposed instrument is fully self-contained in an 8 cm × 4 cm × 15 cm package weighing approximately 0.6 kg. It is built around a miniature integrated gas chromatograph (GC) consisting of a capillary column, a sample injection valve, and detector. A state-of-the-art integrated circuit microcomputer is included in the instrument to handle control and data processing functions. The proposed instrument will be capable of sampling the atmosphere automatically once a minute for eight hours, measuring the concentrations of up to 10 different vapors simultaneously to within 10% accuracy, calculating and storing the time-weighted-average and peak concentrations for each of the gases, measuring concentrations at the 10 ppm level, displaying any of the stored concentrations upon demand, and sounding an alarm when any concentration exceeds a predetermined value. The desirable features of this instrument--its small size, automatic operation, and ability to monitor multiple gases--should make it a useful analytical tool and of significant use in the fields of industrial hygiene and occupational safety.

INTERACTION OF ELECTROMAGNETIC AND ACOUSTIC WAVES IN A STOCHASTIC ATMOSPHERE
by Nirdosh Bhatnagar

JSEP ONR N00014-75-C-0601
NASA NGL 05-020-014
Final Report
July 1977

ABSTRACT

In the Stanford Radio Acoustic Sounding System (RASS), an electromagnetic signal is made to scatter from a moving acoustic pulse train. Under a Bragg-scatter condition, maximum electromagnetic scattering occurs. The scattered radio signal contains temperature and wind information as a function of the acoustic pulse position.

In the theoretical work on RASS to date, the effects of such atmospheric parameters as turbulence, humidity, mean temperature, and mean wind fields on the propagating acoustic pulse train have been ignored. By neglecting these parameters, the quantitative analyses have assumed that the acoustic wavefronts act as large perfect spherical reflectors. In this investigation, RASS performance is assessed in a real atmosphere where "coherency" of the acoustic pulse is degraded as it propagates vertically into the lower atmosphere. The only assumption made is that the electromagnetic wave is not affected by stochastic perturbations in the atmosphere.

Coherency of vertical acoustic-wave propagation is described through a perturbation-theoretic method and Feynman's diagrammatic technique. One of the most important attributes of this analysis is that it systematically and explicitly accounts for multiple scattering of acoustic waves in the presence of atmospheric fluctuations. The coherency results are then used to evaluate the strength of the scattered electromagnetic signal from the acoustic pulse train while taking into account the presence of turbulence, mean temperature gradients, and mean wind fields.

It is concluded that, for acoustic pulses with carrier frequencies below a few kilohertz propagating under typical atmospheric conditions, turbulence has little effect on the strength of the received radio signal at heights up to a few kilometers. This result implies that focusing of RF energy by the acoustic wavefronts is primarily a function of sound intensity which decreases as x^{-2}, where x denotes altitude.

The effect of mean vertical wind and mean temperature on the strength of the received signal is also demonstrated to be insignificant. Mean horizontal winds, however, shift the focus of the reflected electromagnetic energy from its origin, resulting in a decrease in received signal

level when a monostatic RF system is used. For a bistatic radar configuration with space-diversified receiving antennas, the shifting of the acoustic pulse makes possible the remote measurement of the horizontal wind component.

A SILICON ABSOLUTE PRESSURE TRANSDUCER FOR BIOMEDICAL APPLICATIONS
by Timothy Alan Nunn

NIH N01-HD 3-2774
NASA NGR 05-020-690
TR No. 4610-1
October 1977

ABSTRACT

Accurate measurement of pressure is important for many diagnostic, surgical and patient care procedures and also for the control and interpretation of many types of physiological research experiments. To accurately measure these pressures a transducer that was smaller, more stable and less expensive than currently available units was desired.

A silicon absolute pressure transducer has been developed which meets this need. The miniature transducer (1.0 mm × 1.25 mm × 0.4 mm) can be totally batch fabricated using integrated circuit processing techniques, thus yielding a low cost device. The pressure transducer consists of a silicon chip, containing a silicon diaphragm with p-type resistors diffused into it, which is hermetically sealed to a glass cap. An anodic bonding process is used for this sealing and results in a very stable bond. The use of inherently stable materials resulted in a pressure transducer that was very stable with time. The long-term drift has been measured as being less than 1 torr per month.

Analysis of the stress patterns on the silicon diaphragm combined with analysis of the piezoresistive effect resulted in positioning and orienting the p-type resistors so as to maximize the transducer pressure sensitivity. The sensitivity of this device (17 $\mu V/V_s$/torr) is very high, especially considering its small size.

An analysis of the effect of resistor junction depth on pressure sensitivity shows that this effect can be substantial for miniature transducers. The sensitivity decreases as a linear function of the ratio of junction depth to diaphragm thickness. For maximum sensitivity the resistor junction depth should be less than 10% of the diaphragm thickness.

The silicon absolute pressure transducer has been tested both in vitro and in vivo. Results of extensive in vitro testing have shown that the transducer meets or exceeds all the criteria for a pressure transducer used for chronic implants. Results of acute in vivo testing have demonstrated that the pressure transducer, packaged for biomedical use, could survive the rigors of surgical implantation and give accurate pressure recordings. As a result of these experiments, it is felt that the

silicon absolute pressure transducer will find widespread use in many biomedical applications.

KITCHIP--A SUPERIOR
LOW-POWER MONOLITHIC
DEVICE ARRAY
by Stephen Richard Combs

NIH P01 GM17940-06
TR No. 4958-6
December 1977

ABSTRACT

Custom integrated circuits (ICs), compared to discrete component designs, substantially reduce size and power consumption while improving performance, reliability, and device matching. They require sizeable development time and expense, however, and, as a result, are not feasible for small-scale low-production volume applications. These shortcomings are alleviated by a new quick cost-effective monolithic array of unconnected transistors, resistors, and MOS capacitors called a KITCHIP that can be transformed into virtually any simple digital or analog circuit configuration with a single customizing aluminum interconnect pattern. Two KITCHIP arrays described in this report are tailored specifically for low-power biomedical telemetry systems for which no commercially available ICs exist. A bipolar KITCHIP has been applied in 25 different circuit designs, resulting in a bidirectional CW blood flowmeter, a six-channel physiological parameter telemetry system, micropower command receivers, and an ingestible gastrointestinal telemetry pill.

Essential device characteristics for currents between 1 μA and 1 mA typical of these battery-powered systems are high transconductance, good low-current cutoff frequency, and minimal noise. A comparison of bipolar npn, JFET, NMOS, DMOS, and VMOS transistor performance under common photolithographic constraints identifies bipolar and VMOS devices as best suited to biotelemetry applications. Based on this conclusion, an advanced integrated-circuit technology featuring two novel complementary bimodal transistors, whose MOS or bipolar operation mode is determined by the metal interconnection pattern alone, is developed and implemented in a second monolithic KITCHIP array. Electrical characteristics of these transistors and related KITCHIP devices are analyzed in terms of the physical parameters of their vertical impurity profiles, and an impurity distribution optimized for biomedical telemetry applications is derived on a layer by layer basis. The resulting n-type bimodal transistor features a 1 μ double-diffused channel length, a 1 V threshold voltage, and bipolar current gain of 200. P-type transistor characteristics are only slightly inferior.

An eight-mask fabrication sequence presented for realization of these profiles employs ion-implantation for excellent control of electrical performance, low-temperature masking oxidations to minimize unwanted diffusion, and self-aligning techniques to reduce parasitic capacitance. Approximate solutions for processing parameters under arbitrary performance criteria are deduced from given graphical relationships. Novel bimodal KITCHIP device designs and die layout which utilize computer-aided artwork for accurate geometry matching, incorporate techniques for enhancing flexibility and versatility such as scaling of geometry-dependent transistor parameters and preintegration of key circuit configurations. With the bimodal KITCHIP, the operation mode of the device, its transconductance, the ratio of MOS to bipolar parts, and their relative placement across the die are all uniquely determined by the metal interconnection pattern alone.

Each 4 mm square bimodal KITCHIP die contains nearly 300 transistors, over 14.5 MΩ of ion-implanted resistors, 120 pF of MOS capacitance, and three device interconnect levels. It has a unique ability to integrate circuit designs combining linear, quasi-linear, digital, and analog-multiplex functions on a single IC in a quick reliable cost-effective manner.

ALGEBRAIC AND COMBINATORIC
ASPECTS OF CRYPTOGRAPHY
by Stephen Carl Pohlig

Fannie & John Hertz Fd.
NSF Grant ENG 10173
TR No. 6602-1
October 1977

ABSTRACT

One-way functions are functions which are easily computed but difficult to invert. These functions have several uses in cryptography. They can be used to provide a user authentication system that is secure against theft of the password list, and they are necessary to the existence of cryptographic systems which must withstand a known plaintext attack.

Exponentiation over finite fields is a candidate one-way function, and in addition can be used to provide a cryptosystem which is secure against a known plaintext attack if and only if the inverse function, logarithms (indices) over finite fields, is difficult to compute. For the finite field GF(p), where p is prime, the best previously published algorithm requires $O(p^{1/2})$ complexity in both time and storage to compute a logarithm. Two improved algorithms for computing logarithms over GF(p) are presented. They restrict the choice of p if exponentiation over GF(p) is to be a one-way function and are useful in applications which require the computation of logarithms over GF(p). One of these algorithms requires only $O(\log^2 p)$ complexity in time and storage for certain primes p.

One of the algorithms for computing logarithms over finite fields requires the solution of systems of linear congruences mod N where N is a composite number. An algorithm is developed for solving these congruences. Upper and lower bounds are derived for the fraction of matrices which have inverses mod N (i.e. systems of congruences which have unique solutions).

Another candidate one-way function is the knapsack problem, taken from the class of NP-complete problems. In order for this function to be difficult to invert, restrictions must be placed on the choice of the knapsack. Several such restrictions are derived.

Finally, several methods for cryptanalyzing simple rotor (cipher) machines are presented for known plaintext and ciphertext-only attacks. Equivalence classes of rotors are also investigated.

A SIMULATOR FOR THE
EVALUATION OF DIGITAL
SYSTEM RELIABILITY
by Peter Alan Thompson

NASA Grant NGR 05-020-699
NSF Grant MCS 76-05327
AFOSR Grant 77-3325
TR No. 119
August 1977

ABSTRACT

This report describes a simulation package designed to evaluate the reliability of digital systems. The simulator can be used to model many different types of systems, at varying levels of detail. The user is given much freedom to use the elements of the model in the way best suited to simulating the operation of a system in the presence of faults. The simulation package then generates random faults in the model and uses a Monte Carlo analysis to obtain curves of reliability. Three examples are given of simulations of digital systems which have redundancy. The difference between this type of simulation and other simulation techniques is discussed.

A STUDY OF THE "PENINSULA METHOD" FOR THE CONTROLLED ARTIFICIAL GENERATION OF ULF WAVES IN THE IONOSPHERE AND MAGNETOSPHERE

by A. C. Fraser-Smith,
O. G. Villard, Jr.,
and D. M. Bubenik

ARPA Order No. 1733
(A10 and A11)
through ONR Contract
N00014-75-C-1095
Task Area NR 089-121
TR No. 4207-7
December 1977

ABSTRACT

This report presents the results of an investigation of a proposed method for the controlled artificial generation of ultra-low-frequency (ULF) hydromagnetic waves, primarily of class Pc 1 (0.2 to 5 Hz), in the ionosphere and magnetosphere. The basis of this method, which is called the "peninsula method" (a second possible method, the "VLF method," is discussed in a companion report), is the passage of a ULF-modulated electric current around a relatively nonconducting peninsula in the sea or in a large saline lake to form a ULF current loop that produces a ULF magnetic field in the lower ionosphere. Provided the amplitude of the ULF magnetic field fluctuations is sufficiently large, i.e., provided the maximum magnetic moment of the peninsula current loop is greater than about 10^{13} Am^2, it is predicted theoretically that ULF hydromagnetic waves can be generated in a disturbed region of the lower ionosphere above the peninsula. These waves can then propagate away to large distances in the ionosphere and magnetosphere.

The peninsula method is a version of a particular class of ULF wave generation methods based on the use of large ground-based ULF current systems. Compared with other possible methods of generation, these methods appear to have the advantage of reliability and versatility. However, both the construction costs and the power requirements for these systems are large. The peninsula method is particularly attractive because it would minimize these latter disadvantages.

Experiments conducted in 1975 and 1976 with a small peninsula on Chappaquiddick Island, Massachusetts, show that the sea (or salt) water surrounding a peninsula can indeed function as a conducting loop and that this loop can be used to produce ULF magnetic fields above the peninsula. A modeling study based on the results of these experiments indicates that the peninsula method is very efficient: the magnetic field produced at E region height by an electric current flowing through the sea water surrounding the peninsula can be up to 49 times larger than the magnetic

field that would be generated by the same current flowing through a wire loop laid along the shoreline of the peninsula. In addition, because of the low resistance of the sea water path, the power required to drive the current through the sea water around the peninsula can be more than an order of magnitude smaller than the power required to drive the same current through the wire loop. Thus the magnetic field produced per unit of input power is substantially higher for the peninsula current loop than it is for a large horizontal wire loop on the ground. The estimated cost of constructing a peninsula ULF generator is found to be over an order of magnitude less than the estimated cost of a horizontal wire loop system of similar capability. We conclude that the peninsula method of ULF wave generation is feasible and that further experiments, particularly a full-scale ULF generation experiment, are desirable.

STIMULATION OF ULF GEOMAGNETIC PULSATIONS BY CONTROLLED VLF TRANSMISSIONS INTO THE MAGNETOSPHERE

by A. C. Fraser-Smith, R. A. Helliwell, T. F. Bell, T. L. Crystal, and B. Dingle

ARPA Order No. 1733
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ABSTRACT

This report presents the results of an investigation of a proposed method for the controlled artificial generation of ultra-low-frequency (ULF) hydromagnetic waves of class Pc 1 (0.2 to 5 Hz) in the ionosphere and magnetosphere. In this method, which is called the "VLF method," a large ground-based very-low-frequency (VLF) transmitter is used to stimulate the ULF waves by injecting pulses of VLF waves into the magnetosphere. A second possible method of ULF wave generation, the "peninsula method," is discussed in a companion report. In the VLF method, the basic stimulation frequency is the pulse repetition (or modulation) frequency, which is chosen to fall in the ULF range. Stimulation of ULF waves may also occur at any of the harmonics of this basic frequency, depending on the magnetospheric and ionospheric conditions at the time, or it may conceivably occur at a nonharmonic frequency if the conditions are particularly favorable and the generation process produces a high level of broadband ULF hydromagnetic noise.

Theoretical and experimental progress with the VLF method has been encouraging. Theoretical progress includes (1) computer simulation of the cyclotron resonance interaction, which is believed to play a key role in both the ULF generation mechanism and the amplification of VLF and ULF waves, (2) completion of a theory for ULF wave generation based on the repetitive precipitation of energetic electrons into the ionosphere by periodic VLF pulses from a ground-based transmitter, and (3) development of a method for computing the fluxes of energetic electrons precipitated by VLF waves in the magnetosphere.

Experimental progress includes the completion of several long-duration VLF transmission experiments using the 100 kW transmitter at Siple Station, Antarctica. Although it does not yet appear possible to stimulate ULF waves on demand using this VLF transmitter, our experiments suggest that VLF transmissions from Siple could alter the occurrences

of Pc 1 pulsations at Roberval, Quebec, which is geomagnetically conjugate to Siple Station. Because the Pc 1 pulsation events that occur at Roberval can also probably be observed on many occasions over much of North America (and, by inference, over the equivalent conjugate area in the Southern Hemisphere), our experiments suggest that VLF transmissions into the magnetosphere from a single appropriately-located transmitter can influence ULF activity over a large area of the earth's surface. Thus, further experiments appear to be justified.

Combining the theoretical and experimental results obtained during this research, it is suggested that naturally-occurring repetitive VLF activity can stimulate Pc 1 pulsation events, and it is further suggested that such VLF activity may be a major source of stimulation for Pc 1 pulsations. Thus, future experiments on ULF wave generation with ground-based VLF transmitters would probably benefit greatly if they were combined with a program of simultaneous observations of naturally-occurring VLF and ULF activity.

A CCD PHASED-ARRAY
ULTRASONIC IMAGING
SYSTEM
by James T. Walker

PHS Grant P01 GM17940
Dept. of Health,
Education, and Welfare
TR No. 4956-3
December 1977

ABSTRACT

In medical diagnostics, it is extremely useful to have available an instrument that can produce real-time images of organs in the human body. Such a device enables detailed investigation of heart motion and facilitates transducer placement for maximum image quality. Low-power ultrasonic waves used as the sensing radiation make possible noninvasive examination without any known patient risk.

The principal objective of this research is the development of an electronically scanned phased-array ultrasonic imaging system based on CCD delay elements. Charge-coupled devices can achieve variable analog-signal delays with large time-bandwidth products on a small silicon chip, and they are the key factor in the potential realization of a compact flexible imaging system. The phased array contains 31 piezoelectric transducers and a separate transmitter and receiver for each element. Every receiver incorporates a CCD to synthesize electronically the equivalent of a lens focused on the desired object point. Additional circuitry sums the element outputs, controls array scanning, and generates the display. The results are the synthesis of an ultrasonic beam pattern sweeping over a 60° planar sector in the body and an oscilloscope display of the received ultrasonic echoes from a cross section of the human organ.

Doppler beam distortion caused by dynamic focusing and phase-modulation sidebands resulting from nonuniform clocking of a CCD have been analyzed. It has been found that the doppler effect increases system resolution slightly at near ranges and lowers the average echo frequency.

An experimental system operating with 25 active channels has been tested, and measured beam patterns are presented. It utilizes continuous variations of the CCD delay with clock frequency to produce dynamic focusing. The multiplicative algorithm, optimized for single-input/single-output CCDs, obtains real-time scan generation and control.

A MINIATURE INTEGRATED
CIRCUIT ACCELEROMETER FOR
BIOMEDICAL APPLICATIONS
by Lynn Michelle Roylance

NASA Grant
NGR-05-020-690
TR No. 4603-2
November 1977

ABSTRACT

Integrated circuit fabrication technology has permitted the development of an accelerometer weighing less than 0.02 gm, in a $2 \times 3 \times 0.6$ mm package. The accelerometer is intended for biomedical applications such as measurement of heart wall motion and intrauterine motion, where extremely small mass is necessary to avoid measurement artifact. In addition, such applications require a transducer which will detect accelerations down to 0.01 g over a 100 Hertz bandwidth, with an upper acceleration limit of 50 g.

The accelerometer is a glass-silicon-glass sandwich whose active element is a very thin (15 μm) cantilevered beam of silicon. A silicon or gold mass is mounted at the free end of the beam. A 200 μm thick silicon supporting rim surrounds the beam and the mass, providing the built-in end condition for the cantilever and space for contacts. A resistor diffused into the top surface of the beam changes its value with acceleration due to the stress induced in the beam. A second resistor, placed in an unstressed region, is used for temperature compensation. Wells etched into the glass caps, which are hermetically sealed to the supporting rims using anodic bonding, form a cavity completely enclosing and protecting the beam. Fabrication is a batch process utilizing standard IC photolithographic and diffusion techniques, plus anisotropic etching of silicon, to shape the accelerometer.

Experimental results agree closely with the theoretically derived dependence of output on acceleration. The observed resistance change is proportional to the applied acceleration, and depends on the length, thickness, and width of the beam, and on the magnitude and placement of the mass. The dependence on beam geometry allows the sensitivity to be readily varied over several orders of magnitude yet remain tightly controlled. Increasing the sensitivity is shown to decrease proportionally the maximum acceleration the accelerometer can withstand. The resonant frequency also drops, reducing the useful bandwidth. These limitations are, however, equally applicable to other strain gauge accelerometer designs. The miniature accelerometer's frequency response is basically that of an ideal two-pole system, with the resonance typically between 500 and

2500 Hertz. Although the damping factor is only 0.005 with air in the beam cavity, 0.7 critical damping can be achieved with the addition of a fluid.

Accelerometers with sensitivities varying from $\Delta R/R = 5 \times 10^{-5}$ to 2×10^{-3} per g have been fabricated, so accelerations less than 0.001 g can be detected. The corresponding operating ranges are ± 200 g to ± 30 g. The miniature accelerometers compare very well with the small strain gauge accelerometers available commercially, while providing more than an order of magnitude reduction in volume and mass. The small size of this accelerometer, coupled with its performance and the low cost potential of batch fabrication, makes it extremely attractive for biomedical use.

DOMAIN WALL MOTIONS IN
YTTRIUM ORTHOFERRITE
by Ching H. Tsang

ONR Contract
N00014-75-C-0290
TR No. 5307-1
December 1977

ABSTRACT

For the past several years we have carried out a series of experimental and theoretical investigations of domain wall motions in yttrium orthoferrite, which is a low-loss, high mobility canted-antiferrimagnetic material. Using modified versions of the Sixtus and Tonks transit time technique, we measured the domain-wall velocity versus applied H field behavior of Bloch, Néel, and Head-to-Head walls in bulk single-crystal bars of $YFeO_3$ for values of applied H field as high as 100 o.e. wall velocities as high as 10^6 cm/sec and at temperatures varying from 200°K to 600°K.

Experimental results on single crystal bars 1 mm in cross section and 50 mm long show that the velocity vs field characteristics for all three types of wall display a well-defined low field region where velocity varies linearly with H, hence characterizable by a differential mobility μ. We find μ to be approximately 6×10^3 cm/sec-o.e. for both Bloch and Néel walls but appears to be 4.2×10^4 cm/sec o.e. for the Head-to-Head wall, several times larger than for Bloch or Néel walls. Existence of a linear V-H region suggests that the dominant damping process in the bulk are linear ones. When temperature is increased, mobility, μ, for all 3 types of wall is found to diminish monotonically.

In addition, velocity, v, for all 3 types of wall saturates at a common value of $V_s = 4.2 \times 10^5$ cm/sec and remains pinned to V_s until H applied becomes very large (>750 o.e.). This phenomena was then discovered to be a result of strong interaction between the moving wall and the acoustic waves in the solid when velocity of the wall approaches the propagation speed of the acoustic modes.

In the process of analyzing our experimental results, we carried out a systematic computation of spin-wave spectra for $YFeO_3$ and found that, for the case of the uniformly magnetized material, two types of magnon modes are present; a rocking mode (σ) and a twisting mode (γ). When any of the 3 types of domain walls are present, each magnon mode splits into two branches, a free spin-wave branch of high excitation energies and a bounded wall-excitation branch of relatively lower energies. Similarities of the magnon spectra in the presence of these 3

different types of wall lead us to conclude that the Gilbert damping parameter α which describes the magnitude of energy loss in wall motion would be very much the same for all these 3 cases.

Magnetostatic energy analysis then reveals that the Head-to-Head wall is actually slanted at an angle $\theta = 78°$ in the sample bar; and such a slanting can be shown to produce exceptionally high apparent velocities and mobilities. We compensated for such amplification effects from slanting and found that the Head-to-Head wall is actually very similar to Bloch and Néel Walls in its low-field behavior. Magnetostatic analysis also shows that, for the particular size and shape of our sample, the Bloch and Néel walls would experience an effective internal field of magnetostatic origin, propelling them forward even when the external field is zero. This leads to an anomalous zero-field propagation of Bloch and Néel walls which was also observed experimentally. We suppressed these magnetostatic effects by changing the shape and size of our sample and obtained decisive V-H data for the Néel wall from a temperature of 145°K to 390°K. These results, from earlier analysis, are expected to be very close to those for Bloch and Head-to-Head wall also. In particular, wall mobility at room temperature is

$$\mu \cong 1.2 \times 10^{4} \text{ cm/sec-o.e.}$$

Corresponding to a Bloch relaxation time of

$$T_B = 1.8 \times 10^{-10} \text{ sec}$$

Domain wall mobility is then observed to follow quite closely a $1/T^2$ dependence as temperature is changed.

Finally, using the Holstein-Primakoff transformation techniques, we calculated relaxation rates of the uniform precession mode due to intrinsic magnon scattering processes in a uniform canted 2-sublattice $YFeO_3$ system. The calculation showed that the lowest order intrinsic processes that lead to relaxation of the uniform mode are the 4-magnon processes, relaxation processes which do have a T^2 temperature dependence in good agreement with our experimental findings. In particular, estimates of the relaxation rate at room temperature also leads to a Bloch relaxation time

of $T_B \cong 4 \times 10^{-10}$ sec, which is quite close to our experimental value, considering the various approximations used in this calculation. Lastly, our calculations also showed that it is the scattering of 2 σ-mode magnons into 2 γ-mode magnons, brought about by nondiagonal terms of the isotropic exchange energy in the $YFeO_3$ Hamiltonian that constitutes the dominant contribution to the 4-magnon process relaxation rates that we calculated.

ENCAPSULATION AND ANNEALING
OF ION IMPLANTED SELENIUM
IN GaAs
by Alexander Lidow

Army Res. Off., Durham
Contract DAHC-75-G0156
TR No. 4734-2
December 1977

ABSTRACT

A method is described by which GaAs may be encapsulated to withstand annealing temperatures over 1100°C using a double layered encapsulant consisting of arsenic doped silicon dioxide on top of plasma deposited silicon nitride. Samples encapsulated in such a manner and annealed show no signs of mechanical failure and yield higher electrical activation of ion implanted selenium when compared with samples annealed with silicon nitride only. In addition, there is no detectable outdiffusion of Ga or As and no detectable indiffusion of Si. Peak electrical activation of ion implanted Se has been measured as 1.0×10^{19} carriers/cm^3 for samples annealed at 1100°C. A first order strain analysis of general multilayered systems is also presented, indicating possible improvements on such an encapsulating procedure for GaAs as well as other compound semiconductors. The development of this encapsulant is shown to be essential for the study of diffusion of ion implanted elements in GaAs such as selenium.

Electrical measurements are combined with the technique of secondary ion mass spectrometry (SIMS) in order to experimentally analyze and correlate the diffusion and activation of ion implanted selenium in GaAs. Four chemically different species of selenium are identified: (1) substitutional selenium, (2) interstitial selenium, (3) selenium complexed with a gallium vacancy, and (4) precipitated selenium. It is the interactions between these four that dictates resulting redistribution and electrical activation of implanted layers. The factors governing these interactions are investigated, and it is demonstrated that only substitutional selenium is a shallow donor. In addition, it is shown that the species responsible for redistribution of impurity profiles is the selenium-gallium vacancy complex. Precipitated and interstitial selenium appear to neither diffuse nor act like donors in GaAs.

A model is developed which formalizes these observations in a set of five coupled differential equations. By employing a minimum number of simplifying assumptions, we are able to extract quantitative predictions from this model which accurately describe not only our experimental results but those of other workers.

IMPLEMENTATION AND ERROR
ANALYSIS IN DIGITAL
FILTERS BASED ON DIGITAL
INCREMENTAL COMPUTERS
by Ahmad Irsan Abu-el-haija

NASA Grant
NGL 05-020-014
TR No. 3208-8
December 1977

ABSTRACT

Sensitivity and roundoff errors can seriously limit the application of recursive digital filters in practice, particularly when the filters have poles near $z = +1$. A filter structure, based on digital incremental computers, is proposed which has low sensitivity, good error characteristics, and simple hardware implementation for pole locations close to $z = +1$.

The coefficients of the new structure and the "conventional" one are related by linear transformations, resulting in low sensitivity. The low roundoff error is a result of a closed-loop scheme used in truncating the outputs of the integrators and incremental multipliers. The low order bits are not dropped but saved for use at the next epoch. A second-order digital filter implemented by the new structure has two arbitrary gain constants, which allow some freedom in the design, and can be used to reduce roundoff errors and limit cycle oscillations.

For digital filters working in the audio-frequency range, the new structure can be implemented without any hardware multiplier. Also, for a wide range of digital filters, excellent results can usually be obtained using multipliers with very short word lengths. These can be conveniently replaced by small size read-only memories, allowing very high sampling rates.

The accumulation of roundoff errors is more severe for digital filters used for processing differentially pulse-code modulated (DPCM) signals. The new structure can be directly used to process DPCM signals with very low roundoff errors.

Formulas for the sensitivity and roundoff errors are derived and compared with those for conventional structures. Detailed analysis of limit cycle oscillations is made using a "deterministic" approach, and the formulas obtained for limit cycle bounds were in perfect agreement with results obtained by extensive simulation.

A design procedure is suggested to implement the new filter structure given the transfer function to be realized, and the relations among roundoff errors, dynamic range, and the size of the hardware multiplier

are discussed. Implementing high-order digital filters is also considered and simulation results are presented.

In short, the new structure was found to be "matched" to transfer functions which have all their poles clustered around $z = +1$.

THE STRUCTURE OF DIRECTLY EXECUTED LANGUAGES: A NEW THEORY OF INTERPRETIVE SYSTEM DESIGN

by Lee W. Hoevel and
Michael J. Flynn

Dept. of Energy under
EY-76-S-03-0326-PA 39
Army Res. Off.-Durham
DAAG-29-76-G-0001
TR No. 130
March 1977

ABSTRACT

This paper concerns two important issues in the design of optimal languages for direct execution in an interpretive system: binding the operand identifiers in an executable instruction unit to the arguments of the routine implementing the operator defined by that instruction; and binding operand identifiers to execution variables. These issues are central to the performance of a system, both in space and time.

Historically, some form of "machine language" is used as the directly executable medium for a computing system. These languages traditionally are constrained to a single "n-address" instruction format; this leads to an excessive number of "overhead" instructions that do nothing but move values from one storage resource to another being imbedded in the executable instruction stream. We propose to reduce this overhead by increasing the number of instruction formats available at the directly executed language level.

Machine languages are also constricted with respect to the manner in which operands can be "addressed" within an instruction. Usually, some form of indexed base-register scheme is available, along with a direct addressing mechanism for a few, "special" storage cells (i.e., registers, and perhpas the zeroth page of main store). We propose a different identification mechanism--based on the Contour Model of Johnston. Using our scheme, only N bits are needed to encode any identifier in a scope containing less than 2**N distinct identifiers.

Together, these two results lead to directly executed language designs which are optimal in the sense that: (1) k executable instructions are required to implement a source statement containing k functional operators; (2) the space required to represent the executable form of a source statement containing k distinct functional operators and v distinct variables approaches F*k + N*v--where there are less than 2**F distinct functional operators in the scope of definition for the source statement, and less than 2**N distinct variables in this scope; (3) the time needed to execute the representation of a source statement containing k functional

operators, d distinct variables in its domain, and r distinct variables in its range approaches d + r + k; where time is measured in memory references.

TESTING FOR SINGLE
INTERMITTENT FAILURES
IN COMBINATIONAL CIRCUITS
BY MAXIMIZING THE PROBA-
BILITY OF FAULT DETECTION
by Jacob Savir

IBM Grad. Fellowship
and NSF Grant
MCS 76-05237 A01
TR No. 145
September 1977

ABSTRACT

Intermittent faults in combinational circuits may appear and disappear randomly, hence their detection requires many repeated applications of test vectors. Since testing reduces the time available for computation, it is necessary to efficiently minimize the time required for a test while still achieving a high degree of fault detection.

This paper presents an optimal algorithm to detect intermittent failures. The algorithm maximizes the probability of fault detection by optimally choosing the input vector probabilities.

TESTING FOR MULTIPLE
INTERMITTENT FAILURES IN
COMBINATIONAL CIRCUITS BY
MAXIMIZING THE PROBABILITY
OF FAULT DETECTION
by Jacob Savir

IBM Grad. Fellowship
and NSF Grant
MCS 76-05237 A01
TR No. 146
September 1977

ABSTRACT

In present day integrated circuit technology, many faults cannot be modeled as single faults, and the assumption of multiple faults is necessary. Since the class of intermittent failures constitutes a major part of all field failures, a detection procedure for multiple intermittent faults is extremely important.

This paper presents an optimal fault detection experiment for multiple intermittent faults in combinational circuits. The optimality criterion used is maximizing the probability of fault detection. The optimal experiment is achieved by applying input vectors with an optimal probability distribution.

TESTING FOR INTERMITTENT FAILURES IN COMBINATIONAL CIRCUITS BY MINIMIZING THE MEAN TESTING TIME FOR A GIVEN TEST QUALITY

by Jacob Savir

IBM Grad. Fellowship
and NSF Grant
MCS 76-05237 A01
TR No. 148
September 1977

ABSTRACT

Since the cost of detecting and isolating intermittent faults in digital systems comprises a major part of the total testing cost, efficient methods to detect them are required. This paper proposes an optimal algorithm for testing for intermittent faults in combinational circuits which are vital parts of any computing system. The underlying optimality criterion is to minimize the mean testing time and still guarantee a given escape probability. This goal is achieved by applying input vectors with an optimal probability distribution.

MANUAL FOR A GENERAL
PURPOSE SIMULATOR USED
TO EVALUATE RELIABILITY
OF DIGITAL SYSTEMS
by Peter Alan Thompson

NASA Grant
NGR-05-020-699
Supplement 1
TR No. 132
August 1977

ABSTRACT

A simulation technique has been developed for the reliability evaluation of arbitrarily defined computer systems. The main simulation program is written in FORTRAN IV and requires no changes to simulate many different systems. The user defines a model for a particular system by supplying a set of short FORTRAN subroutines and a specially formatted block of numerical parameters. The subroutines specify the functional behavior of various subsystems comprising the model, while the numerical parameters describe how the subsystems are interconnected, their time delays, what faults occur in each one, etc. The main simulation program uses this model to perform a Monte-Carlo-type evaluation of the systems' reliability.

This report supplements a basic description of the technique by supplying all the details necessary for writing subroutines, specifying numerical parameters, and using the main simulation program. The simulation is event-driven and automatically generates pseudo-random faults and time delays according to parameters given by the user. Some problems typical of event simulators, such as ambiguities arising from random time-delay generation, can be solved by taking advantage of special facilities built into the simulation package. A complete source listing of the main program is included for reference.

VERIFYING CONCURRENT
PROGRAMS WITH SHARED
DATA CLASSES
by Susan Owicki

JSEP Contract
N00014-75-C-0601
TR No. 147
August 1977

ABSTRACT

Monitors are a valuable tool for organizing operations on shared data in concurrent programs. In some cases, however, the mutually exclusive procedure calls provided by monitors are overly restrictive. Such applications can be programmed using shared classes which do not enforce mutual exclusion. This paper presents a method of verifying parallel programs containing shared classes. One first proves that each class procedure performs correctly when executed by itself, then shows that simultaneous execution of other class procedures can not interfere with its correct operation. Once a class has been verified, calls to its procedures may be treated as uninterruptible actions; this simplifies the proof of higher-level program components. Proof rules for classes and procedure calls are given in Hoare's axiomatic style. Several examples are verified, including two versions of the readers and writers problem and a dynamic resource allocator.

A STRUCTURED DESIGN
AUTOMATION ENVIRONMENT
FOR DIGITAL SYSTEMS
by W. M. vanCleemput

JSEP Contract
N00014-75-C-0601
US Army Ball. Miss.
Def. Adv. Tech. Ctr.
Contract DASG60-77-C-0073
and Tektronix Foundation
Technical Note No. 134
December 1977

ABSTRACT

This paper describes a design automation system for digital systems that promotes a structured design approach both in logic design phase and in the physical implementation phase.

INITIAL DESIGN CONSIDERATIONS FOR A HIERARCHICAL IC DESIGN SYSTEM

by W. M. vanCleemput
and E. A. Slutz

JSEP Contract
N00014-75-C-0601
Tech. Note No. 132
November 1977

ABSTRACT

This paper describes the initial design of a comprehensive hierarchical integrated circuit design system, that is currently being implemented at Stanford University. This system encourages the use of structured hardware design techniques. It is intended for the design and layout of large-scale integrated circuits by means of a combination of manual and algorithmic techniques.

DUAL REDUNDANCY - A SURVEY
by M. D. Beaudry

NASA Grant
NGR 05-020-699
IBM Grad. Fellowship
Tech. Note No. 93
April 1977

ABSTRACT

This survey covers a wide range of analytical models of dual redundant systems. In such systems two modules, each capable of performing the system functions, are used to increase the overall system reliability. One module is active, while the other operates in a standby mode. The models describe modules with and without repair capability. The analysis of these models gives us the following information about the system:

(1) the system reliability,

(2) the mean time before system failure, and

(3) the availability of the system.

The models depend upon a variety of parameters used to describe the system including:

(1) the system coverage, i.e., the probability that the system continues to function after the active module fails,

(2) the probability distribution of the time until recovery or repair is completed,

(3) the probability distribution of the switchover time,

(4) the failure rates of control and switching mechanisms, and

(5) the duration and frequency of tests or checks of the systems operation.

The analytical results from these models are given in this survey and their relevancy to dual redundant computing systems is discussed. Several computer systems are described to demonstrate the range of applicability of dual redundancy.

PROBABILISTIC TREATMENT OF
DIAGNOSIS IN DIGITAL SYSTEMS
by M. L. Blount

NSF Grant
MCS-05327
Tech. Note No. 102
August 1977

ABSTRACT

The problem of self-diagnosis of multi-unit digital systems is considered in this paper. Each unit can test another unit and/or be tested by another unit. The system test consists of running and compiling test results from all unit tests in the system. As a result of the system test, a decision is made regarding the fault status, faulty or fault-free, of each unit. A model for performing automatic diagnosis in an n-unit system was presented in the much referenced paper by [Preparata, et al, 1967].

In this paper, procedures are developed for calculating probabilistic diagnosability measures for systems that can be modeled in the graph-theoretic diagnosis model of Preparata. The Preparata model is extended in two important ways. Self-testing units can be modeled; the uncertainties and imperfections of the testing process can be modeled. Algorithms are given for calculating 1) the probability that a specified fault condition is correctly diagnosed and 2) the probability that correct diagnosis is performed when a system test is done. Also, a procedure is given for deriving a diagnosis strategy that results in optimal system-wide diagnosability.

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