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Meeting Reports

Transformations in Optical Signal Processing, Battelle Seattle Conference Center, 22–25 February 1981

Reported by William W. Stoner, Science Applications, Inc.

Twenty-three signal processing enthusiasts from the optical and digital worlds recently exchanged viewpoints and insights in a gathering sponsored by SPIE under a newly created Advanced Institute Program. Under the leadership of **William T. Rhodes** (Georgia Institute of Technology) the organizing committee (**Ronald N. Bracewell** and **Joseph W. Goodman** of Stanford University, **Lawrence N. Mertz** of Lockheed, and **Harper J. Whitehouse** of NOSC) charged participants with creating for publication a cohesive volume of individual contributions each treating complementary facets of the institute's theme, Transformations in Optical Signal Processing. The committee and the contributors seek to instill in this volume (now in preparation) the spirit of Mertz's inspired book *TRANSFORMATIONS IN OPTICS*. The Institute volume will address both dimensional and domain transformations.

In optical signal processing, 1-D to 2-D transformations are required to exploit the 2-D information handling capacity of light beams, lenses, spatial light modulators, and array detectors. The best known example of such transformations is raster formatting of a 1-D signal into 2-D, an operation which makes the television industry possible. The raster formatting technique is also used to store a long signal record for high resolution spectral analysis; the 2-D Fourier transform of the raster formatted signal yields the signal spectrum in a raster format known as the folded spectrum.

Rhodes, in the opening talk of the Institute, developed the folded spectrum concept emphasizing the essential unity between the new acoustooptical time-integrating architectures and the older space-integrating approach. Correlation of long 1-D signals is also made possible by formatting over 2-D. In a joint contribution with **W. J. Miceli** (RADC/ET) and **F. A. Horrigan** (Raytheon), your reporter showed how the cylinder (or the torus) provides the geometrical basis for a 1-D to 2-D transformation useful in optical signal correlation and matched filtering.

The role of dimensional transformations in digital signal processing is often disguised but in fact parallels the use of dimensional transformations in optical signal processing. For example, the secret of the fast Fourier transform's (FFT) success is a dimensional transformation that takes a 1-D sequence of $M = 2^N$ data samples and regards it as if it were N-dimensional data with $(M/2)$ pairs of samples along each dimension. The Fourier transform of each individual sample pair (represented by a single butterfly) involves just a sum (the dc part) and a difference (the ac part). A direct consequence of this dimensional transformation is that the operation count scales as $M \log_2 M = MN$ (M butterfly operations along each of N dimensions) instead of M^2.

The fast Fourier algorithm is not directly applicable to data sampled over a polar grid. This has posed a problem to scientists who encounter polar formatted data in CT scanning and in radio astronomy. Bracewell pointed out that the solution to this problem seems to depend on the nationality of the scientist, since the approaches accepted or rejected in different countries vary from smearing to grid interpolation to sample rearrangement. Bracewell's own solution has a Stanford flavor which he hopes will gain international favor.

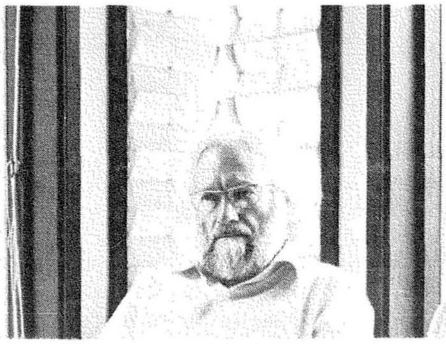
The computational efficiency of digital sampling and fast Fourier algorithms over 2-D were treated by **R. M. Mersereau** (Georgia Institute of Technology); his message is that hexagonal sampling strategies reduce sampling requirements when the 2-D data are isotropic.

Two-dimensional time-frequency representations of 1-D signals were treated comprehensively by **M. J. Bastiaans** (Eindhoven Technical U.). Such representations are of interest to quantum mechanical theory (Wigner) and signal processing (Gabor, Woodward). **T. Kooij's** (DARPA) delightful discussion concerned the Woodward ambiguity function with emphasis on optical techniques for real-time ambiguity surface generation. General time integration architectures for 2-D processing including 2-D (fine and coarse axes), Fourier analysis of 1-D signals, and ambiguity function generation were authoritatively presented by **T. Turpin** (Department of Defense). Real-time 2-D processing is made possible by using a pair of orthogonal 1-D acoustooptical Bragg cells to illuminate a 2-D integrating detector. Whitehouse suggested that a good way to think about such architectures is to use the linear algebraic concept of a vector outer product: the outer product forms a rank 1 matrix out of a row vector and a column vector. Since the sum of N linearly independent rank 1 matrices is a matrix of rank N, as new data flow into each Bragg cell the detector gradually builds up by linear superposition a genuine 2-D output, even though it is illuminated at any instant with rank 1 data.

B. E. A. Saleh (U. Wisconsin) showed how transformations may be used to exchange a quadratic nonlinearity for a more tractable bilinear relationship in two auxiliary variables. Since an optical processor possesses two spatial degrees of freedom, this 1-D to 2-D transformation permits a linear optical processor to accommodate a single quadratic nonlinearity.

Optics is directly applicable to the processing of 1-D or 2-D data, but what about 3-D or generally N-D data? How may such data be formatted for an optical processor? This question was treated by three speakers. **J. Hofer-Alfeis** (Technical U. Munich) presented an ingenious technique which operates upon parallel 2-D slices of a 3-D object. The 2-D slice data presented to the optical processor resembles a strip of motion picture film in which successive frames contain 2-D slices cut progressively deeper and deeper into the original 3-D object. **H. H. Barrett** (U. Arizona) presented the dual


The participants in the Institute.



Richard Bates of U. Canterbury, N.Z. (left) and R. Mersereau of Georgia Tech.

Adold Lohmann of U. Erlangen (left) and A. Sawchuk of U. Southern California.

method—instead of using 2-D slices, he used 2-D projections. Barrett's talk was illuminated with handy operator identities which tied together the Fourier, Hankel, and Abel transforms. **A. Lohmann** (U. Erlangen-Nürnberg) examined the question with a characteristically original approach. He first introduced the abstract concept of a dimensional transducer (which might involve projection, slicing, raster formatting, etc.). Then a general data processing framework was developed which employs dimensional transducers to interface the data processor with the outside world.

To round out this session **T. S. Huang** (U. Illinois) shared with the Institute his research on motion estimation of complex 3-D scenes from sequences of 2-D images.

Optical domain transformations were discussed by J. W. Goodman, A. A. Sawchuk, and H. J. Caulfield. Goodman presented a generalization of the coherent optical Fourier transformation which encompasses Laplace transforms. A potential application of this novel 1-D to 2-D (complex plane) optical transformation is polynomial evaluation. **B. R. Frieden** (U. Arizona) observed that related computations involving the poles of rational functions are of interest in maximum entropy and autoregressive estimation. **A. A. Sawchuk** (U. Southern California) covered intensity to spatial frequency transformations with applications to parallel A-D conversion and level slicing of optical images. A panoramic view of optical domain transformations was presented by **H. J. Caulfield** (Aerodyne).

Transformations which iterate between domains (Gerchberg-Saxon iteration) have grown in popularity because many problems of an optical nature are constrained in both the space and frequency domains. **J. Fienup** (ERIM) presented a masterful account of the wide scope of problems tractable through domain iteration and imparted some practical experience with his own enhancements of the Gerchberg-Saxon algorithm. **R. Marks** (U. Washington) gave a scholarly presentation on the application of iteration of extrapolation of bandlimited functions, and presented some numerical simulations which Frieden noted are in agreement with noise sensitivity predictions based upon prolate spherical function analyses.

In the quest of capturing image details which are beyond the seeing disk, astronomers have been aided by optical techniques developed by A. A. Michelson and by A. Labeyrie. Neither of these approaches yield true images, providing instead autocorrelation structure because both techniques throw away phase information. Attempts have been made to use domain iterative techniques to unravel the autocorrelation functions; **R. H. T. Bates** (U. Canterbury) and **L. Mertz** offered a different tack. They contend that the full image information is present in the atmospherically perturbed photon stream available to the astronomer, and that phase information preserving operations should be applied to the data, so that it never becomes necessary to unravel an autocorrelation function to recover the phase. The approach of Bates involves a remarkably simple shift and add technique which has been effective in laboratory simulations. Mertz's algorithm requires knowledge of the photon arrival sequence, stimulating his colleagues and he to develop an x, y, and t (time) photon detector.

R. O. Schmidt (ESL Inc.), **H. Whitehouse**, and **K. Bromley** (NOSC) imparted their insights into future signal processing directions. An intriguing signal subspace approach to multiple emitter location utilizing data collected by a sensor array was presented by Schmidt. Matrix concepts play a central role in this very promising technique. The universality of matrix concepts and matrix operations in modern signal processing was stressed by Whitehouse and Bromley. Their review of the present status of analog parallel processing of vector and matrix data led to the observation by Whitehouse that VLSI chips provide a new opportunity for the optical signal processing genius, since the quest for increased computational throughput demands VLSI parallel processing architectures which are remarkably similar to optical processing and surface wave processing architectures.

TRANSFORMATIONS IN OPTICAL SIGNAL PROCESSING is being edited by J. Fienup, B. E. A. Saleh, and W. T. Rhodes. It is scheduled for publication in late 1981.

The photographs were provided by W. T. Rhodes.