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In this final report we summarize our research accomplishments under this grant: (a) research on our multiresolution estimation methodology to solve a variety of difficult image and large-scale data assimilation problems and to extend the theoretical domain of applicability of our methodology considerably to allow for the fusion of multisensor datal.; (b) the development of several new methods involving synthetic aperture radar (SAR) data including multiresolution segmentation and compression algorithms and an estimation-theoretic approach to moving target SAR image formation; (c) the development of a new nonlinear multiresolution image evolution algorithm that produces extremely robust image segmentations; (d) the development of a new variation on so-called matching pursuit methods with application to robust and stable feature extraction and recognition of objects; and (e) the development of hierarchical and wavelet-based methods for the design of joint detection algorithms for multiple access communication in the presence of highly correlated user signals. In addition a number of significant transitions and interactions resulting from our work are described.

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Final Technical Report for
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MULTIRESOLUTION METHODS IN SYSTEMS, SIGNALS AND IMAGES

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I. Summary: Objectives and Status of Effort

In this report we summarize our accomplishments in the research program supported by Grant AFOSR–95-1–0083. The basic scope of this research program was to carry out fundamental research in several interrelated areas: (a) the use of multiresolution methods in statistically optimal image analysis; (b) the development of a methodology for multiresolution data fusion and inversion with applications in several areas; (c) the development of computationally efficient and nearly-optimal estimation and prediction algorithms for extremely large-scale space-time data assimilation problems arising in remote sensing applications; and (d) the development of multiresolution and wavelet-based methods for multi-access and/or secure communications, for robust detection of abrupt changes in signals and systems, and for nonparametric system identification. Key features of this project were that (i) it blended together methods and issues in several fields, namely signal and image processing, systems and control, and large-scale computation; and (ii) each aspect of the program contained both fundamental research in mathematical sciences *and* important applications of direct relevance to Air Force missions. The principal investigator for this effort was Professor Alan S. Willsky. Professor Willsky was assisted in this effort by Dr. Hamid Krim, a research scientist in MIT's Laboratory for Information and Decision Systems, and by several graduate research assistants as well as additional thesis students not requiring stipend or tuition support from this grant.

During the tenure of this grant we had considerable success both in our basic research and in providing techniques and results of use to DoD programs and contractors, and we summarize these in the following sections of this report. In the next section we describe our research accomplishments; in Section III we indicate the individuals involved in this effort; in Section IV we list the publications supported by this effort; and in Section V we discuss interactions and transitions.

II. Accomplishments/New Findings

In this section we briefly describe the research accomplishments we have achieved under this grant. We limit ourselves here to a succinct summary of the most recent of these results and refer to the publications listed at the end of this report (as well as the previous progress reports) for detailed developments.

Multiresolution Statistical Modeling and Estimation Methodology

The research described in this section is reported in a number of papers and reports [9, 15-21, 27-29, 36, 50-54, 57, 58, 69-76]:

(1) Dr. Michael Daniel and Prof. Willsky recently completed a first effort on extending our multiresolution modeling methodology to allow for nonlocal measurements--i.e., to allow for measurements at differing resolutions. These measurements show up as local measurements in our framework, but at different resolutions in our multiscale representation. As a result, our very efficient methods for optimal data assimilation allows us to fuse these different data sets with the same efficiency as for the processing of a single data set. A significant part of the contribution of this effort is the characterization of the property of statistical consistency. Specifically, if a particular nonlocal variable is represented at a coarse-scale node in our multiresolution representation, then there is a precise way in which this information must be propagated to descendent nodes. We have now shown that this method can be used both for the fusion of very different sets of sensor data and for the fast and statistically optimal solution to complex inverse problems. In particular, one invited paper on the theory behind this method has now appeared, and a second paper on the application of this method to problems in groundwater hydrology is nearing completion. The latter is significant for the Air Force, as the driving application is the assessment of long-term subterranean storage of radioactive material. In performing this last effort, we have had to deal with substantial nonlinearities in the underlying equations and have developed effective ways in which to determine when the approximations implied by linearized physics are insignificant compared to other sources of uncertainty and variability. In particular, we have demonstrated the full capabilities of this methodology in estimating the travel time for particles (e.g., of radioactive material) to exit from a bounded region based on a sparse, irregular, and heterogeneous set of measurements of subsurface properties. Furthermore, our estimation algorithm not only produces estimates but also provides error variances for those estimates, based on the linearized physics incorporated in the multiresolution models. We have demonstrated through extensive simulation (using the full, nonlinear physics) that these error variances

represent extremely accurate measures of estimate quality. Given that these error variances require orders of magnitude less computation than simulation of the physics, this is a very significant result.

(2) The work of Dr. Daniel and Prof. Willsky has also deepened our understanding of how to perform multiresolution model construction for fractal-like processes and random fields, also known as 1/f processes and fields or fractional Brownian motions and fields. Such models are widely used both to model real noise processes and to model textures in natural scenes. This work is of significance because fractal models of this type are widely used in practice for discrimination and segmentation, and our approach offers significant computational advantages. We have now completed a major paper on this topic for 1-D signals. The most recent research results that are presented in this paper include; (a) a proof of the self-similarity of the linear functionals of the process that form the optimal state variables in our multiresolution tree; (b) the demonstration of the near shift-invariance of these linear functionals; (c) the use of both of these properties to produce very low-dimensional and very high quality multiresolution approximations to fractional Brownian motions; and (d) the demonstration of the utility of these models for several different problems--conditional simulation, optimal estimation from sparse and irregular samples--for which there had previously been no efficient algorithms.

(3) The investigation by Mr. Terrence Ho, Dr. Paul Fieguth, and Prof. Willsky of the use of our multiresolution methodology for the assimilation of extremely large measurement sets in large-scale space-time and distributed estimation problems. Such problems arise in a variety of applications, ranging from systems and control applications involving processes better described by partial differential equations than by lumped, finite-dimensional models (e.g., heat distributions or dynamics of flexible-winged aircraft) to large-scale data assimilation for remote sensing, important both for military (global spatial databases, weather maps, terrain mapping,...) and nonmilitary (earth resources mapping, basic earth sciences studies, ...) problems. The key challenge in such space-time estimation problems is the propagation in time of a full error covariance for the estimated field. For fields of even modest size, even storing such a covariance matrix is out of the question. Instead we are developing methods for the direct propagation for multiscale models of the errors in these spatial estimates, reducing by orders of magnitude the required storage and calculations. In our initial work in this area we demonstrated that we can do this without statistically significant loss of performance for problems of modest size in both one and two dimensions--i.e., for problems in which we could explicitly construct

the error covariance and then build multiscale models matching the error statistics. While this proves the principle that multiscale models can be used effectively, the real challenge is developing methods for constructing such models *directly*, i.e., without ever having to compute the prohibitively large error covariance for problems of significant size. We have now developed a general approach to this problem and have devised several suboptimal instantiations of its solution. The key here is to deal with the "mixing" caused by the temporal dynamics of the process being estimated. Specifically, to form a multiscale model in which the variables at each node on the multiscale tree are linear functionals of the finest-scale process, we need all of the parent-child covariances as well as the covariances of the state at each node (as these then define the parent-child dynamics). In general, thanks to the structure of the multiscale tree and the local mixing of dynamic models, some of these covariances can be exactly computed as time propagates with minimal computational overhead; however complete calculation of all required statistics is prohibitively complex. Thus, we are faced with a generalized covariance extension problem: given knowledge of some covariances among a large set of random vectors, estimate some of the missing covariances. In our work we have used an approach based on maximum entropy to solve this problem locally on the tree (i.e., we estimate each required covariance element using local knowledge on the tree together with the max entropy principle). The results of this method for 1-D space-time estimation problems are impressive, demonstrating that near-optimal algorithms can be produced with modest computational effort, especially compared to the infeasible optimal estimator. Furthermore, our most recent work in this area have shown that these concepts can be equally well applied in 2-D.

(3) Mr. Michael Schneider, Dr. Fieguth, and Prof. Willsky have finished a research project on adapting our multiresolution methods to produce a new approach to the segmentation of images. As always, the motivation for doing this is the speed of our algorithms, together with the direct availability of error statistics which are provided by our methodology but are essentially impossible to compute for standard variational formulations. We have now demonstrated that our methodology can produce segmentations of equal quality to those produced by standard methods but at a far smaller computational cost and with the added benefit of providing error statistics. In addition, we have demonstrated that the error statistics produced by our algorithm--which are only approximate for this nonlinear problem--do provide accurate measures of uncertainty. In addition, Mr. Andy Tsai and Prof. Willsky have developed a new approach aimed not only at segmentation problems but at other problems in which there are discrete variables (such

as edges, boundaries, anomalous measurements, etc.) to be dealt with in addition to an underlying image or random field of intensity values. Specifically, this effort deals with combining our multiresolution estimation formalism with the expectation-maximization (EM) approach to estimation. The latter approach does provide a useful way in which to solve computationally difficult problems as long as both the "E" and the "M" step of the algorithm can be computed quickly. Our research in this area has demonstrated the promise of this approach for several different problems, including segmentation, edge detection, and the robust processing of laser radar range data in the presence of range anomalies.

(4) Mr. Austin Frakt and Prof. Willsky have recently made significant progress in developing the theory of multiresolution stochastic realization. The two significant conceptual advances are: (a) the development of a scale-recursive theory of realization; and (b) the development of a new estimation-based criterion to replace the canonical correlation-based approach developed previously. Both of these advances have dramatic impacts on overall computational complexity: our new algorithms have complexity that is roughly the square root of the complexity of previous algorithms, allowing us to apply our methods to vastly larger problems.

Image Analysis and Formation with Applications to SAR Imagery

The research described in this section is reported in a number of papers and reports [22-26, 29, 48, 49, 59, 60, 64, 65]. Our recent work has had several components:

(1) The first of these, involving Mr. Charles Fosgate, Mr. Andrew Kim, Mr. John Richards, Dr. Krim, and Prof. Willsky, builds on our earlier research on multiresolution modeling and analysis of SAR imagery. This work is based on the observation that the spatial distribution of scatterers is very different between targets and clutter and between different types of terrain. Consequently, if we form SAR images at a sequence of resolutions, the scale-to-scale variation in imagery should be very different for targets, clutter, and for different types of natural terrain, since the constructive and destructive interference among scatterers within resolution cells, as we vary the dimensions of these resolution cells, should have statistically distinct scale-to-scale characteristics resulting from the differences in scatterer distributions. The value of this concept was first proven in the context of target-clutter discrimination reported previously. More recently we adapted our multiresolution SAR likelihood ratio methods to the problem of distinguishing and segmenting different types of natural terrain (trees, grass, etc.).

(2) The multiresolution SAR modeling methodology described above has also provided us with a method for the enhancement of anomalous pixels--i.e., pixels containing dominant scatterers that do not have the same statistical variability from scale to scale. These scatterers are of considerable importance in characterizing man-made objects and in their recognition. The idea here is that the scale-to-scale residuals produced by our models for such residuals will not be statistically white in scale (as the models would predict) but instead have coherent behavior across scale. By detecting such coherency we can enhance the visibility of such scatterers. We have implemented such a method and have demonstrated its promise as compared to another widely-used anomaly enhancement method, namely the generation of so-called CFAR statistics. These promising results provide the basis for future work on object recognition algorithms that recognize patterns of such scatterers in the presence of speckle.

(3) Our multiresolution models for SAR also suggest a scale-recursive method for SAR image compression. In particular, our models can be viewed as autoregressive (AR) models in scale. This suggests the adaptation of methods for compression of time series using AR models in which data are compressed by storing both (i) an appropriate multiscale model; (ii) a coarse-scale SAR image, appropriately compressed; and (iii) compressed versions of the scale-to-scale prediction errors between model and actual data. A first effort along these lines has very recently been completed in the SM thesis of Mr. Kim, and papers based on this work are currently in progress.

(4) Mr. Cedric Logan, another student of Prof. Willsky's, has continued his research on the problem SAR imaging of moving targets. The starting point for this work involves viewing it as a problem of joint position-velocity imaging--i.e., the SAR equivalent of range-Doppler imaging but now in 4 dimensions (2 space and 2 spatial velocity). This work is being carried out in collaboration with Drs. Krim and Dr. Chaney. Mr. Logan has developed a novel and very efficient method for calculating what can alternatively be thought of as the likelihood function for the location in range-rate/cross range of a scatterer or as an image in this 4-D space. Using this likelihood function he has developed an approach to SAR imaging that does not require motion to be rigid body. Specifically, one of the objectives of this work was to develop a method that can focus an entire SAR image even if different scatterers in the scene are moving differently. We have demonstrated this approach for the focusing of images of independently moving scatterers both in isolation and also embedded into real SAR imagery. These results show the

promise of this approach in providing focused SAR images in contexts in which conventional SAR imaging is severely degraded.

(5) Mr. Austin Frakt and Prof. Willsky have completed the development and study of a method for scale-recursive anomaly detection and localization methods from tomographic data. The objective of this project is to devise a decision-directed mechanism to decide in which areas we should "zoom" in to resolve anomalies in more detail. What we have obtained is a result that we believe is significant well beyond its use in tomography. In particular, in trying to perform zooming, one might imagine forming a low-resolution image and performing detection on it--i.e., using the low resolution pixels as the statistics on which to base detections that would guide subsequent zooming operations. By interpreting the problem as one of composite hypothesis testing, it is not difficult to show that that approach is not optimal--indeed in statistical jargon, there is no uniformly most powerful test. However, it is possible to come up with other statistics that do a better job than that done by forming a low-resolution image. That is, what one does at coarser resolutions is to *image statistics* that are useful for zooming and the statistics that one images may not correspond to lower-resolution images of the phenomenon of interest. What this has led us to consider is the development of statistics that are optimized to maximally separate groups of hypotheses. We have now finished a paper that demonstrates the power of this method and quantifies the performance improvements over naive zooming approaches as well as the performance loss as compared to the prohibitively complex method of exhaustive examination of all anomaly hypotheses.

Nonlinear Multiresolution Image Processing

This component of our research, which is documented in [61, 62, 66], has as its ultimate objective the development of both statistical and multiresolution interpretations of the recent flurry of research activity in nonlinear anisotropic diffusions as well as the development of new algorithms inspired by these interpretations. Our first research in this area, carried out by Mr. Ilya Pollak, Dr. Krim, and Prof. Willsky, began by an examination of some of the basic concepts underlying the use of anisotropic diffusions for segmentation and quickly led to a new nonlinear algorithm that not only leads to vastly reduced computational burdens but also provides explicit segmentations at a hierarchy of resolutions (rather than requiring substantial postprocessing and interpretation). This new algorithm is characterized by a set of coupled differential equations for the transformation of image pixel values, where in our case the differential equations have a significant discontinuity that leads both to robust edge identification and to noise removal, including the removal of high-amplitude noise spikes. We have demonstrated that this algorithm can perform surprisingly accurate segmentations for the very high speckle levels present in SAR imagery. In addition, in our most recent work in this area, we have characterized the performance of this algorithm in segmenting 1-D signals. These results show that these new nonlinear algorithms achieve nearly as good performance as likelihood ratio tests under the ideal conditions of white Gaussian noise (under which likelihood tests are optimal) and are considerably more robust to deviations from this idealized noise model.

High-Resolution Pursuit

Prof. Willsky's Ph.D. student, Dr. Seema Jaggi, recently completed her research (documented in [32, 33, 55]) on robust multiresolution feature extraction through a technique which we refer to as high-resolution pursuit. This work, was carried out in direct collaboration with Prof. Stephane Mallat of Courant Institute. The basic approach that we have developed and described previously is a variation on Mallat's matching pursuit algorithm involving a new criterion that trades off between global fit and local fit in choosing each of a succession of features. This involves only a modest increase in complexity over matching pursuit but leads to features which are much more clearly connected to physical features in data and which appear to have significant robustness to several types of noise, including additive noise as well as "spiky" noise, as one would expect in speckle-corrupted radar data.

Our most recent work involved the application of this method to the problem of recognition of objects from their silhouettes. Specifically, there is a natural way in which to map a silhouette into a 1-D signal corresponding to the outline of the object, and a number of recognition methods have been developed that are based on analyzing these 1-D silhouette functions. These methods all have some deficiencies, notably robustness to noise or to the absence of features or the introduction of spurious features due to noise, occlusion, or anomalous estimation of object silhouette as can occur in practice. The vehicle that we used to test our approach is the recognition of silhouettes of a number of different aircraft, a problem that has been considered by others and which thus provides us with a fair way in which to compare our methods to those developed by others. The results of extensive testing demonstrates the superiority of our new approach, including an increased level of robustness to the types of silhouette errors observed in practice.

The Use of Wavelets and Frames in Multi-user Communication

The research described in this section is reported in a number of papers and reports [37-44, 56, 63]. Our work in this area has focused on investigating several aspects of an extremely important problem in multi-user communication, namely the optimal joint detection of signals from large numbers of users. This research was performed by Prof. Willsky and his former student, Dr. Rachel Learned, together with Dr. Donald Boroson of Lincoln Laboratory. The problems we have examined have been chosen to be of direct relevance to the applications of concern to Dr. Boroson's satellite communication group. In particular this group is keenly interested in developing methods for accommodating additional users on limited communication links. This leads directly to the need to consider situations in which the signals being communicated by the many users may be highly correlated and in fact linearly dependent. In cases such as this, which also arise in multiple access terrestrial communication, there are challenging problems, both in selecting the sets of signals to be used by the users and in designing computationally efficient demodulators that can separate out individual users from the myriad of other signals and noise that are present.

The major innovation in our work has led to a set of user signals that allows optimal multiple access demodulation to be performed in a computationally simple fashion. In particular, by choosing signals with so-called tree-structured correlation, we have shown that optimal detection can be performed with polynomial complexity (in fact, very low-order polynomial complexity). This is a major accomplishment, since for arbitrary signal sets, optimal detection is NP-complete. Our most recent research in this area with Dr. Boroson has led to an extension and adaptation of this method that allows us to deal with synchronization phase errors.

III. Personnel

The following is a list of individuals who have worked on research projects supported in whole or in part by the Air Force Office of Scientific Research under Grant AFOSR–95-1-0083:

Prof. Alan S. Willsky, professor of electrical engineering, MIT
Dr. Hamid Krim, research scientist, MIT Lab. for Information and Decision Systems
Dr. Paul Fieguth, postdoctoral researcher
Dr. Michael Daniel, recent Ph.D.
Dr. Rachel Learned, recent Ph.D.
Dr. Seema Jaggi, recent Ph.D.
Mr. Michael Schneider, graduate student
Mr. Charles Fosgate, graduate student
Mr. Ilya Pollak, graduate student
Mr. Austin Frakt, graduate student
Mr. Terrence Ho, graduate student
Mr. Andrew Kim, graduate student
Mr. Dewey Tucker, graduate student
Mr. Cedric Logan, graduate student
Mr. Andy Tsai, graduate student
Mr. John Richards, graduate student

IV. Publications

The publications listed below represent papers, reports, and theses supported in whole or in part by the Air Force Office of Scientific Research under Grant AFOSR–95-1–0083:

[1] Nikoukhah, R., Taylor, D., Levy, B.C., and Willsky, A.S., "Graph structure and recursive estimation of noisy linear relations," *J. of Math. Syst., Est., and Cont.*, Vol. 5, No. 4, 1995, pp 1-37.

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V. INTERACTIONS/TRANSITIONS

In this section we summarize the various interactions and transitions associated with research supported by AFOSR Grant F49620-95-1-0083.

Participation/Presentation at Meetings

In addition to presentations at professional conferences, as listed in the publications in the preceding section, we have been involved in the following other meetings during the past year:

(1) Prof. Willsky has continued to have regular meetings with engineers and researchers at Alphatech to discuss collaborative research in the area of SAR-based ATR.

(2) In April 1997 Prof. Willsky briefed some of our AFOSR research to Dr. John Hamre, Controller of the Department of Defense, during his visit to MIT.

Consultative and Advisory Functions

During the past year, Prof. Willsky has been engaged in the following activities relevant to the research being performed under our AFOSR grant:

(1) Prof. Willsky has regularly acted as a consultant to Alphatech, Inc. in a number of research projects including ones that represent direct transitions of the technology being developed under our AFOSR Grant. These are described in the next subsection.

(2) Prof. Willsky has also regularly acted as a consultant at Lincoln Laboratories in the area of ATR and in particular in incorporating some of the research resulting from our MIT research into Lincoln's ATR algorithm suite.

Transitions

The following are the transitions of our research that have taken or are taking place:

(1) Our multiresolution methods for estimation of motion vector fields (known as "optical flow") in image sequences has been transitioned to Alphatech, Inc., which applied these, under a Phase II SBIR project with the Weapons Division of the Naval Air Warfare Center (NAWC), as a front-end in an image-based tracking system. The specific application is in terminal missile guidance based on imagery provided by an IR sensor array on the missile. The data is extremely noisy and motion is erratic, as the missile itself undergoes maneuvers, rotation, etc. The point of contact at NAWC is Dr. Gary Hewer. The points of contact at Alphatech are Dr. Robert Washburn, and Mr. Thomas Allen, and Dr. James Huang.

(2) These same optical flow estimation methods are also being used by Alphatech in projects related to the tracking of automobiles for intelligent highway systems. The points of contact at Alphatech are the same as for (1).

(3) Our multiresolution methods for likelihood function calculation and texture discrimination have been transitioned to Alphatech, Inc., which is currently applying these, under a Phase II SBIR project with the ARPA-DSO, to ATR problems, including ones applicable to ARPA-STO's Clipping Service Program. The point of contact at ARPA is

Dr. Anna Tsao. The points of contact at Alphatech are Dr. Robert Tenney, Dr. Robert Washburn, and Dr. William Irving.

(4) Our multiresolution SAR discrimination algorithms have been transitioned to Alphatech which is incorporating them into proposals to DARPA for the development advanced techniques for both model-based ATR and ATR for foliage-penetrating SAR. The points of contact on this are Dr. Robert Washburn and Dr. William Irving (Dr. Irving is the former student of Prof. Willsky's whose Ph.D. research established the basis for our approach to SAR analysis).

(5) Our work on multiresolution SAR analysis and high-resolution pursuit have been transitioned to Alphatech under a Small Business Technology Transfer contract from the Army Research Office to transition our multiresolution mapping and estimation methods to military applications. The points of contact at Alphatech for this are Dr. Robert Washburn and Dr. William Irving.

(6) Our work on multiresolution stochastic modeling has been applied, in direct collaboration with engineers at Lincoln Laboratory, to the enhancement of Lincoln's ATR system. In particular, in this work we have helped Lincoln to build multiscale models of pieces of SAR imagery as the basis for the generation of a likelihood feature that was added to Lincoln's feature set for the discrimination of natural clutter from man-made objects. This effort was highly successful, as described previously. The point of contact at Lincoln Laboratory for this effort is Dr. Leslie Novak of Group 47, Lincoln Laboratory.

(7) We have worked directly with both Lincoln Laboratory and more recently with Alphatech in transitioning and extending our methods for terrain discrimination and anomaly enhancement in SAR imagery using multiresolution models. The points of contact for this are Dr. Ronald Chaney (previously at Lincoln Laboratory and now at Alphatech) and Dr. Alan Chao of Alphatech.

(8) Prof. Willsky has had extensive interactions with engineers at the Charles Stark Draper Laboratory in transitioning our multiresolution modeling, estimation, and discrimination methods to Draper activities and programs. The potential and actual customers for Draper in this effort include NASA (in their Earth Observing System program) and several Air Force programs. Draper has invested some of its own internal R&D funds in this effort, both to support Draper personnel and Prof. Willsky's group. In addition, our recent work on image segmentation is in the process of being transitioned to Draper in connection with a joint project that we have with Draper, Boston University, and Massachusetts General Hospital to develop biomedical image segmentation algorithms. The Draper point of contact is Dr. Homer Pien.

(9) Prof. Willsky and his student, Ms Rachel Learned, have engaged in intensive direct collaboration with Lincoln's satellite communication group in order both to define research problems for our MIT efforts and to provide technology of use to Lincoln in the area of multiple access communication. This effort has now led to a major research result reported in Section II and to several additional research problems that are aimed at addressing significant problems of importance in satellite communications. Lincoln has continued to support Ms Learned's research efforts. The Lincoln point of contact is Dr. Donald Boroson.

(10) Prompted by requests from numerous sources, involved not only in DoD-related projects but also in other projects (primarily in remote sensing), we have made a version of our code available by ftp.

(11) Our recent work on multiresolution SAR compression has just been transitioned to Alphatech.

Other relevant items

(1) Our work has been cited several times in AFOSR's annual Research Highlights publication.

(2) Prof. Willsky and his former student, Dr. Mark Luettgen, have on several occasions prepared briefing materials for presentations made by Dr. Sjogren to Department of Defense personnel, most recently in early 1997,

(3) AFOSR has placed Prof. Willsky's name in nomination for the Air Force Scientific Advisory Board