January 01, 2008

Year Eight Annual Report : 2008

Bernard M. Gordon Center for Subsurface Sensing and Imaging Systems (Gordon-CenSSIS)

Section 7B-1 Strategic Research Plan

1. Three-Level Strategic Plan Structure

Figure 7B-1 illustrates the three-level structure of the Center's strategic plan. Real-world requirements for advanced SSI solutions identified on the Engineered System Level (L3) help determine research and technology barriers. Research thrusts and validating testbeds are structured to address these barriers. Deliverables include new physical probes, data-tested algorithms, and end-to-end integrated instruments that will allow real-world problems to be addressed. In examining Figure 7B-1, we see that feeding into the System Level is a physical and mathematical unifying framework. An intrinsic element of the three-level strategic diagram of Figure 7B-1 is the vertical and horizontal feedback and integration that cements the whole together. Our organization of the research program from this standpoint is described in Section **7B-2**.

A deep understanding of the Center's three-level strategy is necessary to drive the multi-level feedback paths of Figure 7B-1. Over the past eight years, we have refined this understanding through ongoing discussions culminating in annual strategic planning retreats. The results can be summarized into six major points. They are:

The Center's engineered system, I-PLUS, was renamed after the first retreat. The original acronym was "Integrated Probes to Look Under Surfaces". The new acronym is "Integrated Process for Looking Under Surfaces". This highlights our view that I-PLUS is an engineered process that enables multi-

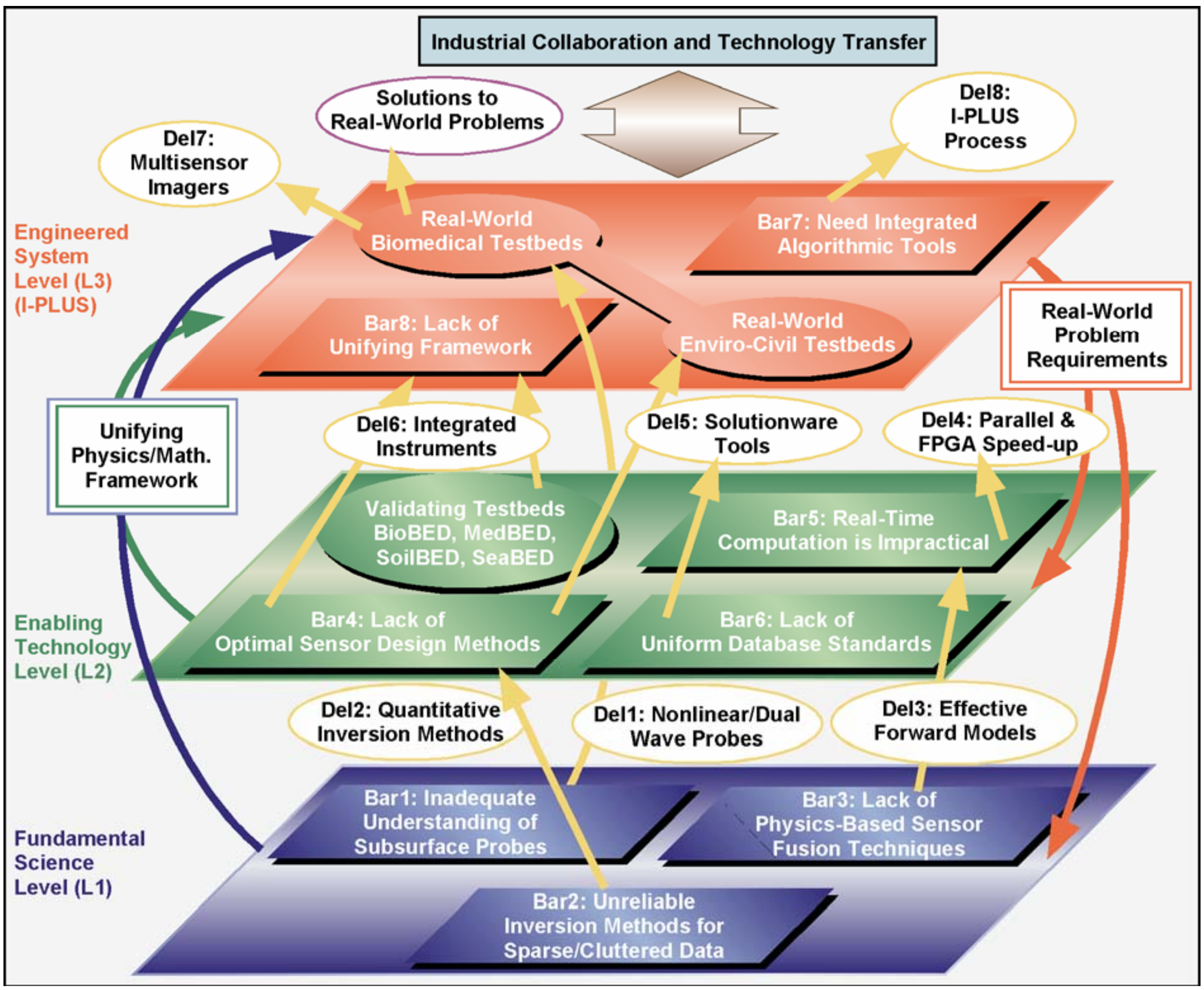

Figure 7B-1. The Gordon-CenSSIS strategic plan allows research to be informed by applications.

disciplinary teams to efficiently arrive at high quality sensing and imaging solutions to important societal subsurface assessment problems.

The "Unified Framework" is more correctly named the "Unifying Framework". The Unifying Framework is classification of a diverse set of subsurface problems into a small number of categories where common solution methods and tools are shown to be effective. This framework is an essential element of the I-PLUS engineered system.

Specific real-world SSI applications are needed to guide the development of the I-PLUS process. At the third year retreat, we determined that the I-PLUS process could only be developed and tested through the study of specific real-world application areas. Moreover, there needed to be several areas considered because of the need to demonstrate the "Diverse Problems, Similar Solutions" aspect of our strategy. Thus in Year 3, we identified five initial "system testbeds" that encompass a range of biomedical and environmental applications. They are discussed further in Section **7B-1C**.

The role of the System Level real-world problem testbeds needed better definition in order to drive the development of I-PLUS. After introducing the system-level testbeds in Year 3, the Center needed to address the issue of how the real-world problems themselves could drive the feedback mechanisms inherent in our strategic plan (Figure 7B-1). Deep discussions on this topic began at the fourth year retreat. It should be emphasized that the implementation of effective system-level testbeds is a research topic in its own right. The Director and Deputy Director of Gordon-CenSSIS have emerged as the leaders of this effort. This has served to strengthen even further the collaborative bond between these two key guardians of the Center's vision and mission.

An undergraduate textbook on Subsurface Sensing and Imaging is a key deliverable for Gordon-CenSSIS this year. See Section **7C** for more details.

Key elements of a sustainable legacy are demonstrations of system-level impacts and the development of externally-funded projects with industrial partners.

1A. Fundamental Science Level (L1)

On the fundamental science level of Figure 7B-1, three research thrusts (labeled R1, R2 and R3) address fundamental barriers and the development of a unifying physical and mathematical framework.

Research Thrust R1 (Subsurface Sensing and Modeling) seeks to elucidate the nature of next-generation sensing mechanisms and the development of realistic physical models. Thrust R2 (Physics-Based Signal Processing and Image Understanding) integrates R1 into robust algorithms to solve the real-world problems. Thrust R3 (Image and Data Information Management) develops efficient computation and reusable software capabilities to link distributed sources of data and implement complex algorithms in near-real-time. Springing from these fundamental studies will be new subsurface probes based on nonlinear material characteristics and dual-wave interactions, efficient and robust inversion techniques for random cluttered media, and advanced fusion and recognition strategies.

The Gordon-CenSSIS mission rests on our observation that the number of information extraction strategies is small compared to the number of individual modalities, and there is sufficient commonality in these underlying physical and mathematical structures to develop a unifying framework. A schematic of this framework is shown in Figure 7B-2. As indicated in the figure, the framework will unify approaches to address all tomographic (multi-view tomography) problems: electrical impedance tomography, diffraction tomography, and diffuse wave imaging. These techniques can be used for a range of diverse applications and spatial scales. A similar methodology applies to the deconvolution and focusing problems associated with LPM and to MSD methods such as optical microscopy systems and hyperspectral sensors. On a more

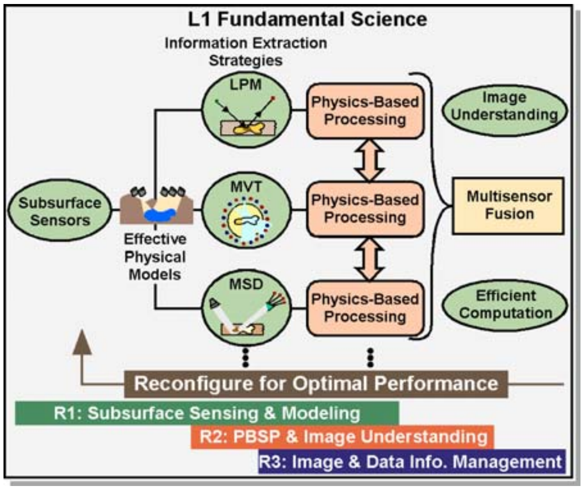

Figure 7B-2. The Unifying Framework will exploit the commonality in subsurface information extraction strategies.

general image understanding level, the difficulties with accurate reconstruction of the required information arise from many sources: sparse, limited data collected at surface boundaries, sensor uncertainties, clutter, and the complex nature of the environment. These elements will also be part of a versatile unifying framework.

We will consider a multi-view tomography (MVT) example to illustrate how the Unifying Framework will allow us to address diverse problems with common tools. Diffuse wave optical tomography for medical diagnosis and crosswell radar/EMI tomography for geophysical exploration both involve extracting an image of, or information about, anomalous regions (e.g., diabetic lesions under the skin or oil-bearing rock formations under the ground; see Figure 7B-3). Although the problems occur

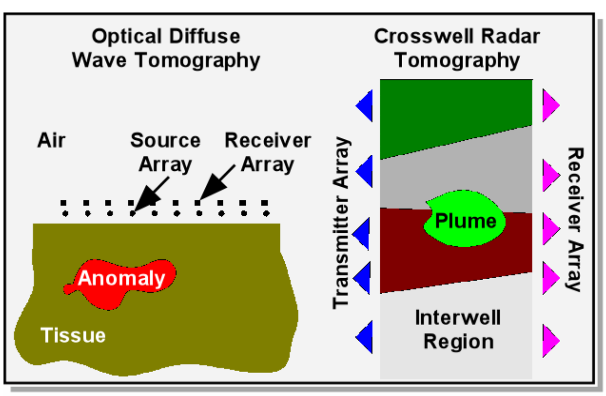

Figure 7B-3. Diverse problems can be addressed with a similar mathematical/physical framework.

on vastly different length scales, both require solution of the frequency-domain diffusion equation in the presence of an inhomogeneous, layered medium, and a need to filter large data sets from multiple transmitters and receivers that are nevertheless sparse compared to the information set sought. Attacking these two problems within the same Center allows the synergy of the two solutions to be exploited.

Thus, even the critical differences between the two problems (lossy vs. lossless propagation, Poisson vs. Gaussian noise statistics, the diffusion equation as a limit of the RTE vs. the diffusion equation derived by neglecting the displacement current in Maxwell's Equations) become a basis for more complete understanding of the unifying approach rather than just an obstacle to applying the same specialized algorithm to each problem. Physics-based reasoning will be used through the entire process, and goal-directed processing will produce algorithms which are robust to modeling errors and generate accurate reconstructions of the critical information.

1B. Enabling Technology Level (L2)

The Enabling Technology Level of the Gordon-CenSSIS strategy allows the engineered system to evolve from fundamental research; new probes are tested with controlled environments and algorithms are verified with controlled and characterized "ground-truth" data. The principal vehicles for this process are validating testbed facilities where well-characterized environments are studied with versatile, controllable, reconfigurable sensors.

The L2 validating testbeds are becoming general Gordon-CenSSIS resources with data available to test models and algorithms at all the ERC institutions.

Four multi-sensor testbeds have been defined (shown in Figure 7B-4) based on physical length scale and the wave propagation qualities (and therefore the available probe modalities) of the media. The structure of a testbed is shown in Figure 7B-5. The application of different modalities to the same experimental en-

Testbed	Length Scale	Media Characteristics
Biological Microscopy (BioBED)	10^{-9}m to 10^{-5}m	Molecules and cells in biological media that range from transparent to translucent for VIS/UV/x-ray
Medical Imaging (MedBED)	10^{-6}m to 10^{-1}m	Tissue structure and organs in tissue media that are highly scattering to both ultrasonic and IR/VIS phototonic probes, and absorptive to transparent for microwave, RF, and lower frequency electromagnetic probes
Underground Imaging (SoilBED)	10^{-2}m to 10^{2}m	Buried man-made objects and geophysical structures in soil and bedrock media that are absorptive and scattering for RF, microwave, and sonic probes
Underwater Imaging (SeaBED)	10^{-1}m to 0^{3}m	Water-column or ocean-floor mariculture and physical structures in atmospheric and seawater media that are absorptive and scattering for optical and sonic probes

Figure 7B-4. Diverse problems can be addressed with a similar mathematical/physical framework.

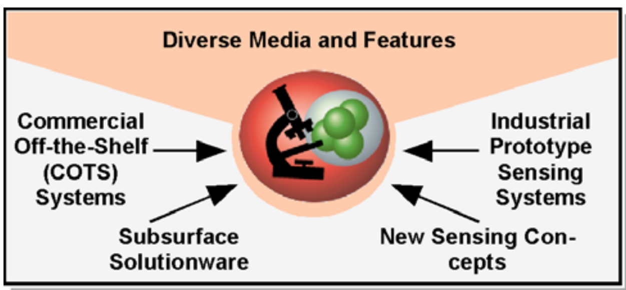

Figure 7B-5. L2 Validating testbeds are centered around controlled environments.

vironment will allow sensor fusion and cross-modality optimization – reconfiguration of one sensor based on information from another.

Solutionware tools are also part of the enabling technology products that support I-PLUS. These consist of suites of modeling, analysis and visualization tools that have proven to be of broad utility in solving large classes of SSI problems. The tools are organized according to the classification determined through the unifying framework. Our legacy will include MATLAB-type tools that can be accessed by a wide community of users. In order to use these products, the users must have technical knowledge. One long-range mandate of our education component is to produce textbooks and manuals that will enable the widespread use of Solutionware.

1C. Engineered System Level (L3)

The Engineered System Level consists of Integrated Solutionware tools and L3 testbeds of real-world applications. A key outcome of this level is the I-PLUS process itself that will enable the rapid assessment and development of cost-effective, high-quality solutions to diverse subsurface problems.

The multidisciplinary integration on the Engineered System Level of the experience collected from a broad range of real world SSI problems can be accessed to the benefit of each new problem. Solutions in one domain will be adapted to create solutions in another domain. I-PLUS will make the “Diverse Problems, Similar Solutions” emphasis of Gordon-CenSSIS work for each user of the engineered system.

The System testbeds shown on Level 3 of Figure 7B-1 consist of experiments that incorporate at least one important societal application in order to test and improve the Unifying Framework, identify common Solutionware tools, create multi-sensor instrument prototypes and refine the structure of the engineered process, I-PLUS. In Year Three, we identified five initial areas to spark the development of I-PLUS. Denoted S1-S5, they are:

- **S1:** The study of cellular reproduction and growth processes using 3-D multi-modal optical microscopy. This work is a collaboration between biologists at NU and MSKCC.
- **S2:** The creation of image-guided therapy approaches that incorporate real-time effects such as respiration. This work is a collaboration with the Radiation Physics Departments at MGH and MSKCC.
- **S3**: The development of multi-modal noninvasive techniques for the screening of incipient breast cancers. These new diagnostics would be used to augment existing x-ray-based methods. Collaboration is with the

Breast Imaging Division of the Department of Radiology at MGH.

- **S4:** A demonstration of the feasibility of using airborne- or satellite-based hyper-spectral imaging augmented by localized *in situ* point measurements to monitor the benthic habitats of shallow and deep coastal waters. A specific focus is on coral reef degradation. This work is a collaboration with marine scientists at WHOI and UPRM.
- **S5**: The use of 3-D multi-sensor instruments to assess the presence of buried contaminants and explosives. This complex task will be accomplished through collaboration with INL and LLNL.

An essential aspect of our system-level strategy is the collaborative links to the Gordon-CenSSIS strategic affiliates. Without the leveraging of domain expertise and external resources the Center would be unable to implement its strategy to the extent needed for the development of I-PLUS. Our research program will be guided by feedback to and from the system level via applications such as S1-S5. More detail on the system-level projects can be found in Volume II.

It is important to emphasize that other system-level application areas will emerge over the years of the Center's evolution. The key again is to leverage external resources, i.e. funding from government agencies and industry.

I-PLUS will enable the classification of societally important problems based on wave propagation, target contrast, and noise/clutter characteristics that have been determined to be relevant to the desired recognition and decision tasks by the Level 1 fundamental research. In cases where relevant acoustic, electromagnetic, or photonic linear or nonlinear/dual-wave processes are unknown, Gordon-CenSSIS enabling technology testbeds may be used to gather the required information. In other cases, industry resources can be used to investigate key material properties identified by I-PLUS. The set of Level 2 testbed-verified forward models and inversion algorithms collected in "Solutionware" will be available to model new problems and determine optimum processing strategies to achieve the application goals.

2. Time Line and Milestones

Figure 7B-6 shows a time line for Gordon-CenSSIS activities over the ERC 10-year horizon. The Center's effort has been enhanced by research activities primarily supported by other associated programs shown in the hexagonal boxes. Fundamental science projects in quantum optical coherence tomography at BU and optical quadrature microscopy at NU will be supplemented by the NSF- and NIH-supported RPI and NU projects on confocal microscopy and the 3-D fusion microscope. These projects coalesced into the L2 3-D Biological Microscopy testbed (BioBED) in the fifth year of the ERC. Clearly this fosters the S1 effort described above. The fundamental ERC work on phase conjugation and time reversal beamforming applied to optics may impact this testbed, while the acoustic applications of this technique will contribute to the medical and underground testbeds (MedBED and SoilBED). Other SSI projects that will evolve into a multi-modal MedBED include work on electrical impedance tomography at RPI, quantitative ultrasound imaging at BU and NU and dual-wave ultrasound/diffusive wave imaging at BU, NU, RPI and MGH. These will be the foundations for the development of S3, the multi-mode breast imaging system testbed based at MGH.

An Autonomous Underwater Vehicle (AUV) has been developed under ONR and NASA support at WHOI. This, combined with the NASA-supported Hyperspectral Remote Sensing research at UPRM, has culminated in SeaBED, the underwater imaging testbed at UPRM, and WHOI. This will then lead to a proof-of-principle demonstration in Years 8-10 of the ability to monitor coral reef health from airborne and satellite based instruments (S4). The real-time tools inherent in this underwater application, coupled with the confocal microscopy registration tools developed for BioBED, will be combined with physics-based change detection algorithms to provide a next-

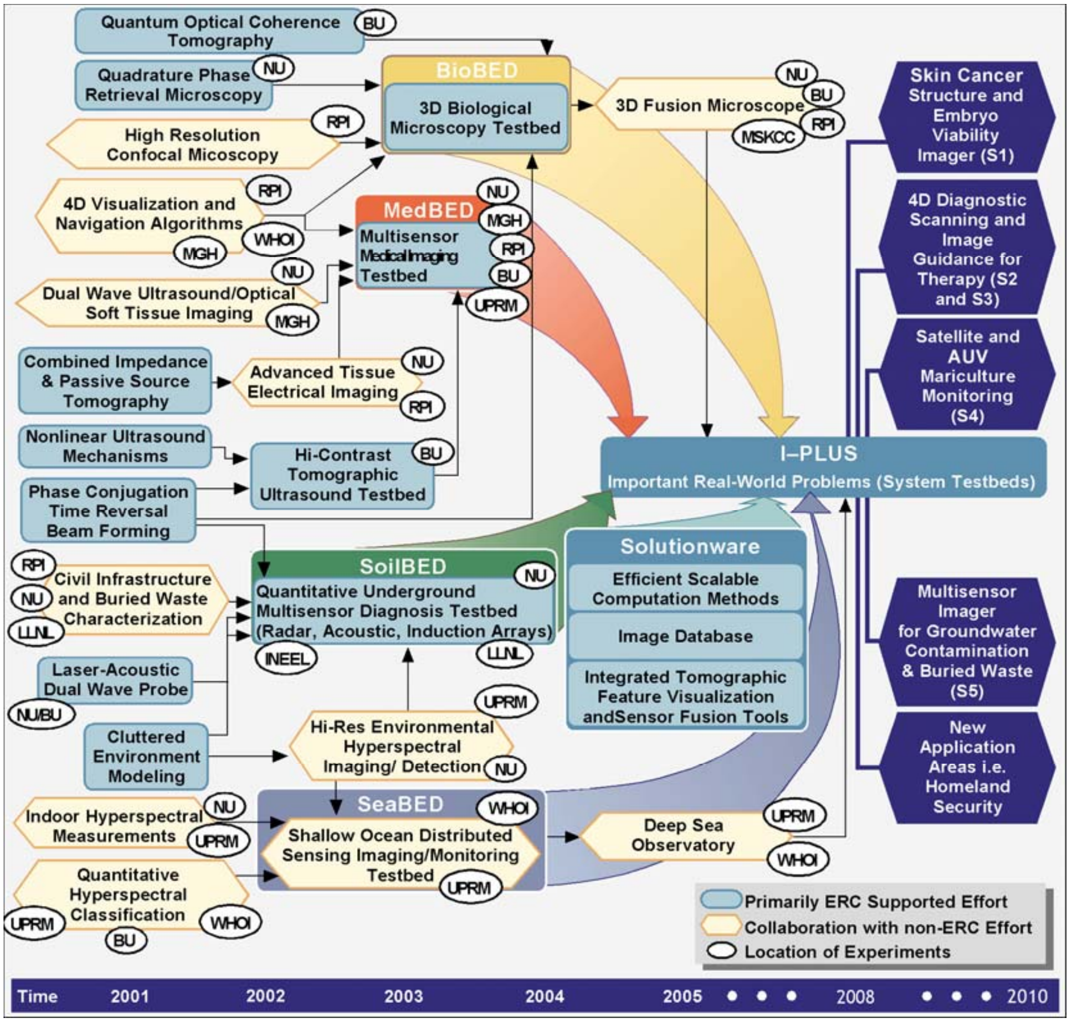

Figure 7B-6. Research and testbed timeline leading to our grand challenge engineered system (I-PLUS).

generation set of tools for image-guided planning of complex radiotherapy of cancer. This use of common tools for a new application is the heart of the application area S2. This demonstration of our "Diverse Problems, Similar Solutions" strategy was enabled by the vision of Dr. George Chen of MGH, who clearly saw the potential of working with Gordon-CenSSIS. The S2 application area is important for robust I-PLUS development because it highlights the need to incorporate real-time dynamics into the SSI algorithms.

Fundamental Science (L1) research in cluttered environment modeling and inversion and GPR imaging of underground objects will continue. This work has also been partially supported though INL, LLNL, and the US Army Night Vision Laboratory. The effort contributes to the evolution of our underground imaging testbed (SoilBED) and to the assessment of areas such as buried contaminants or explosives and civil infrastructure (S5).

By the end of the fourth year of the Gordon-CenSSIS program, the first generation of suites of re-usable algorithms developed for these different applications was collected in a common format as "Solutionware." These algorithms will continue to be refined and validated via the L2 multi-sensor testbeds. The I-PLUS process will be structured by: (1) the four testbeds, (2) the Solutionware library, and (3) lessons learned from the L3 real-world applications S1-S5. I-PLUS will be the vehicle for the revolutionary breakthrough products of the ERC. Some key milestones are summarized in Figure 7B-7.

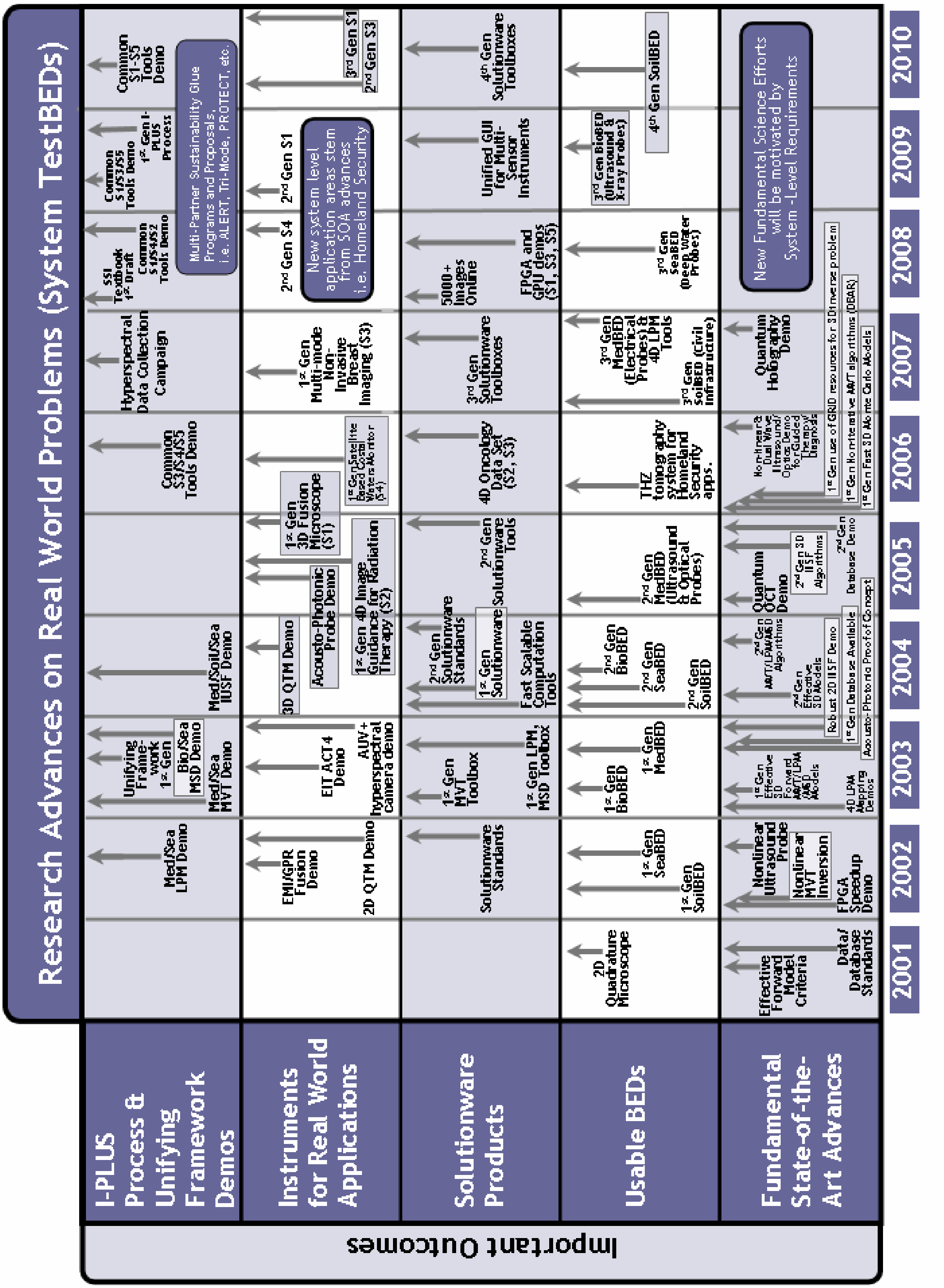

Figure 7B-7. Key Milestones for the research program.