COUPLING AND FUSION IN MODERN GEOSCIENCE

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ABSTRACT

We summarize two projects representative of a developing movement in modern geosciences. By establishing a linkage between the developed coupling simulator and fusion prototype, we successfully incorporate geosciences with informatics, computer technologies and mathematics in the field of data processing. A challenging coupled inversion scheme is shining under such an integration.

Keywords: Data integration, Information fusion, Inverse algorithm, Coupled system, Partial differential equation, Remote sensing, Monitoring technique

1 INTRODUCTION

Multiphysical coupling analysis and multidisciplinary knowledge fusion are increasingly important for solving earth and solar science problems, in particular to meet growing demands for fast processing of huge amounts of information and accurate site-scale numerical simulations. In past decades, different disciplines within the overall geoscientific subject area have used coupling (e.g., numerical modeling of high-level-radioactive-waste disposal repositories) and fusion (e.g., remote sensing data processing) techniques widely, but there has been little interaction between the separate disciplines (e.g., Hudson et al., 2005; Li, 2006; Jiao et al., 2006; Sasai et al., 2005). The principles of mathematics and physics, though, form a common basis for the component disciplines of all geosciences. In recent years, with the conceptualization of multiphysics and the encapsulation of computational mathematics, calls for greater integration of data and knowledge on various spatial-temporal scales have been heard. Intelligent coupling computation and effective information fusion is becoming a key to future discoveries in the geosciences. We envision this subject becoming a truly new research movement or field in the near future, one that will dramatically improve on the traditional approach of only qualitatively characterizing natural systems. In fact, the beginnings of such a trend can already be seen in multidisciplinary and interdisciplinary sciences (e.g., Yeh et al., 2008; Sato et al., 2006).

In this paper, we provide a summary of two projects in this new research field, while shedding some light on the integration of coupling and fusion in a coupled inversion problem using corner-reflector-based satellite synthetic aperture radar (SAR) information and advanced numerical simulation. The goal of the first project was to build an integrated thermal-hydraulic-mechanical-chemical-biological (T-H-M-C-B) multiscale and multiphysics coupled simulation system that can be applied to geological disposal problems (Li et al., 2001; Li et al., 2005; Li et al., 2006a; Li & Ito, 2008). The aim of the second project was to construct a sustainable decision support system for non-renewable resource exploration and geological hazard mitigation utilizing satellite images and geological databases (Sato et al., 2006; Li & Sato, 2007; Li et al., 2007a).

2 FROM COUPLING TO FUSION AND BEYOND

2.1 Coupling simulator

The coupling problem is of wide interest, being applicable to fields ranging from coupled processes associated with the construction of underground openings, subsurface energy extraction, and micro-earthquakes induced by fluid injection, to the assessment of high-level radioactive waste (HLW) disposal repositories and geological sequestration of carbon dioxide. Over the last decade, much progress has been made in theoretical and experimental studies of the effects of the couplings of temperature gradient, hydrogeological flow, mechanical deformation, and geochemical concern. Exploiting the ideas coupling geomicrobiology effects into the mature T-H-M-C model are particularly challenging to geoscientists and mathematical physicists. Research into coupling methods applicable to T-H-M-C modeling of geological disposals has gone on for some time. The international DECOVALEX project initiated in 1992 led to a wide understanding and modeling of coupled T-H-M processes in geologic systems (Tsang et al., 2005). This project has made some important scientific discoveries regarding the development of mathematical modeling and *in situ* testing of coupled T-H-M processes in fractured rock and buffer/backfill materials used for performance assessment of HLW geological repositories.

Although T-H-M coupling processes have been extensively investigated within the DECOVALEX project, the chemical process and geomicrobiological effect have not previously been widely incorporated into the coupled models and codes. In our developed framework (Figure 1) for coupled geological disposal, it is important to integrate the conventional models for some individual physical-chemical phenomena (flow, diffusion, convection, conservation of energy, mechanical and chemical equilibrium) into a strong coupled multiphysical model using finite element methods. Understanding and debugging a complex coupling scheme pose great challenges for geoscientists when a variety of geological factors are involved. The integrated coupling scheme is very strong and flexible when applied to geological disposal problems according to our past experiments (e.g., Li et al., 2005; Li et al., 2006a; Li et al., 2007b). While the details of the coupling models that turn out to be optimal for different problems vary widely, the concepts and fundamental frameworks we describe in this paper provide the basis of the most important coupling approaches published in the literature. Of course, geologic environments are intrinsically complex and heterogeneous, which makes the application of general coupling principles and coupling relations difficult and uncertain in any specific situation. Interested readers can find further details of pertinent theories (e.g., Bai & Elsworth, 2000; Stephansson et al., 2004) and applications in our published (or soon to be published) articles (e.g., Li et al., 2006a).

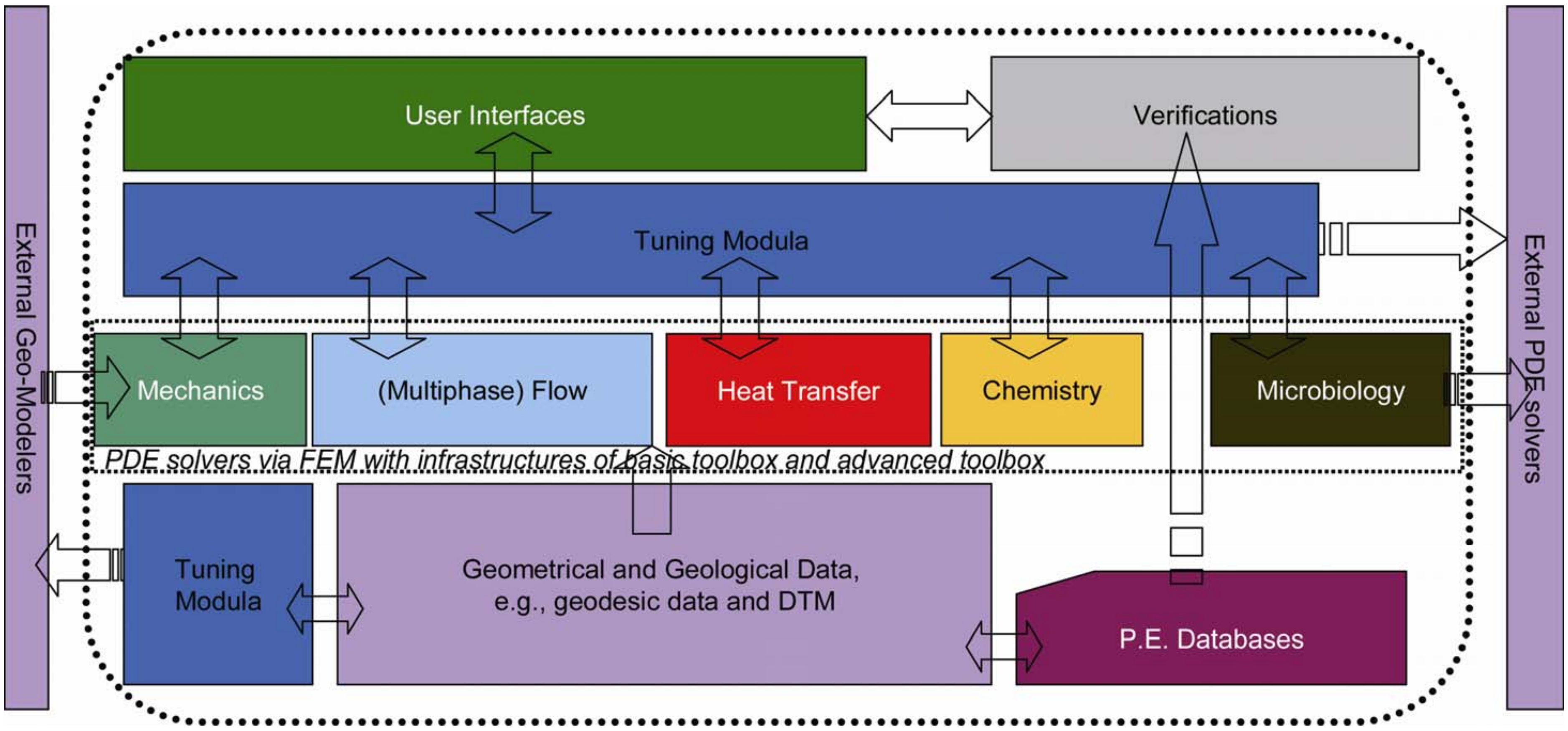

Figure 1. Integrated coupling scheme for thermal-hydraulic-mechanical-chemical-biological multiscale and multiphysics problems

2.2 Fusion prototype

With the flood of data and information now available, information fusion and data mining are becoming urgent topics in modern geosciences. To integrate geology-related data – such as satellite images, airborne photographs, geological maps, and various thematic maps – image registration is the first key step (Li et al., 2006b; 2007c). After multiple satellite remote sensing data are seamlessly integrated with geological data, they can be used for various applications (e.g., Fu et al., 2007). Our information integration process is powered by a prototype system with four cores: automatic registration, classifier, image fusion and enhancement, and change detection. Each core is equipped with state-of-the-art algorithms and has a flexible processing flow via functional modules. The skeleton of our prototype system is depicted in Figure 2. As shown, the optimization module is the heart of all the data processing. In most cases, an iteration process is needed (Li, 2006; Li et al., 2006c; Li et al., 2008). Note that data exchange among the cores can be very complex in scientific information fusion, and a concrete fusion scheme can be tailored by the user using script language according to different needs.

As a potential application of this fusion prototype, change detection is of widespread interest because of its numerous kinds of application in diverse disciplines. Even though there are huge differences between applications as diverse as remote sensing, medical diagnosis, video surveillance and health monitoring of civil infrastructure, approaches to solve each application problem are very similar. Every change detection method employs some basic processing steps and core algorithms. It is usually applied by detecting the difference between two accurately registered images. However, the problem becomes much more complicated when the images to be compared vary with respect to illumination, orientation, imaging modality, etc. In such situations, detecting changes by direct comparison of corresponding pixels is not enough to yield an accurate and applicable result (Li et al., 2007d). Additional processing is needed, such as image enhancing and fusion. Experiments have shown that our developed prototype is flexible and promising. It can easily incorporate our geological missions into the system, and greatly speed up the analysis and decision processing for resource exploration and geohazard mitigation.

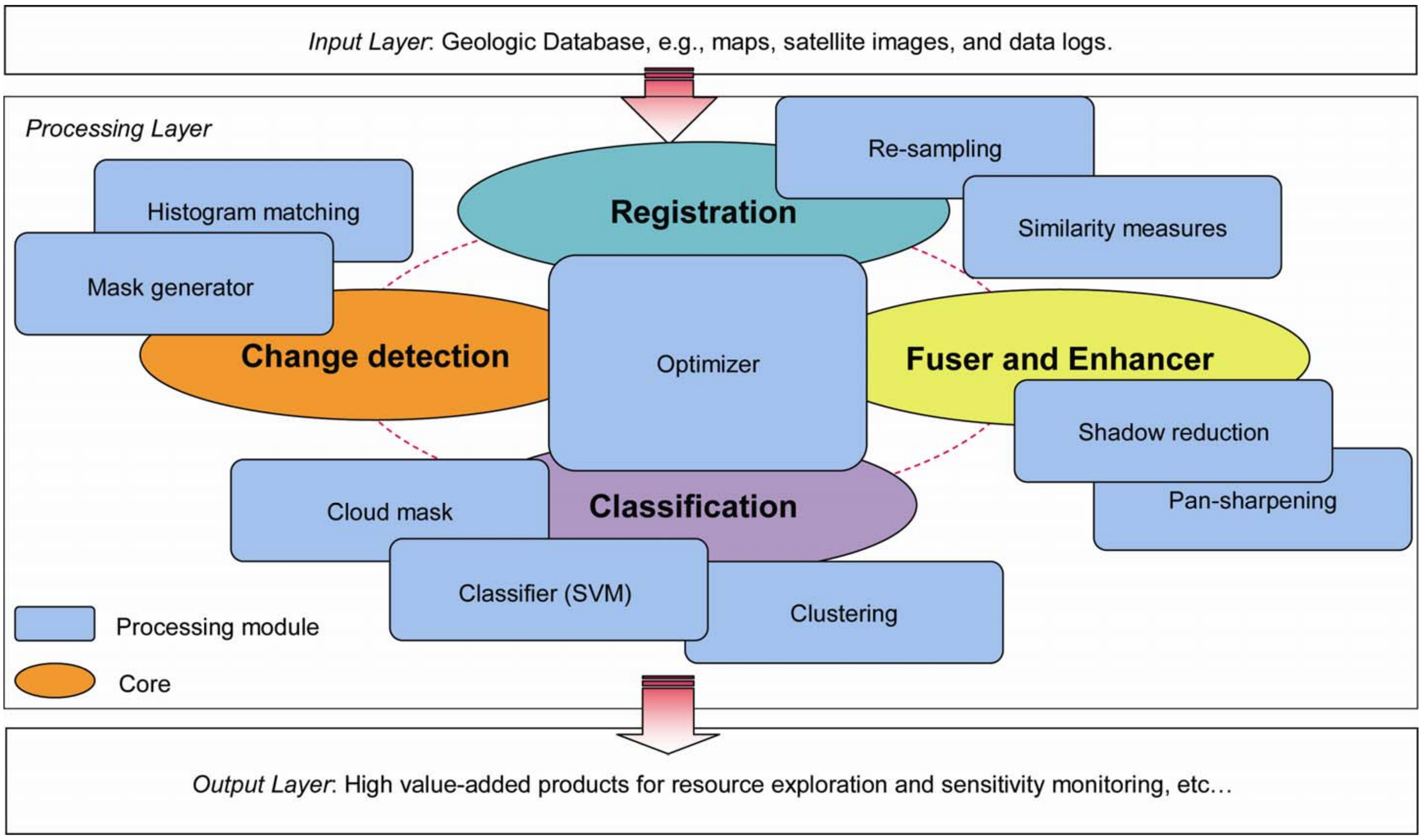

Figure 2. Prototype of geological information fusion for resource exploration and geohazard mitigation

2.3 Coupled inversion using satellite remote sensing monitoring

Technically speaking, most earth and solar science systems are inverse problems. For instance, in hydrogeology accurate predication of subsurface flow and transport relies on detailed knowledge of the spatial distribution of hydraulic parameters

(Cai & Yeh, 2008). However, the subsurface is naturally heterogeneous at different scales. To obtain a detailed spatial distribution of hydraulic parameters for a field problem, a direct measurement method usually requires a large number of measurements at many different locations, which is costly and often impractical. On the other hand, direct and indirect aquifer responses (i.e., hydraulic head, surface deformation) can be easily measured at relatively little expense. These responses can be used to deduce the spatial distribution of hydraulic parameters. However, detailed aquifer characterization using responses still requires a large number of measurements, so cost-effective data collecting techniques are needed. For example, satellite permanent scatterer interferometric SAR (PS-InSAR) detects precise changes of ground height on the millimeter order with cloud-free and day-and-night surface observation. This PS-InSAR based surface deformation can be used as an indirect aquifer response, and satellite PS-InSAR monitoring is likely to be used in the future as a cost-effective data collecting technique (Li et al., 2009).

A particular goal of our research is to create a linkage between the latest PS-InSAR monitoring technology and the T-H-M-C-B coupling simulator (Li & Ito, 2008). The framework of this goal is depicted in Figure 3. Surface deformation due to underground excavation is accurately monitored through geodetic imaging using satellite interferometry (Li et al., 2009). The deformation magnitude is then used to control the startup of the T-H-M-C-B coupling simulation system for inverse modeling to map fluid migration within the Earth. The T-H-M-C-B process is truly coupled, rather than sequentially coupled, to solve the multiphysical partial differential equations by using the finite element technique. In addition to direct hydraulic inversion of permeability and surface deformation for pore volume change, our proposed coupled inversion scheme can incorporate T-H-M-C-B coupling effects into history matching during the evolution of natural systems. Potential applications lie in three major areas of geosciences: 1) assessment of subsurface flow and parameter identification of aquifers, 2) site assessment for nuclear repositories, and 3) reservoir monitoring and characterization, such as for the geological sequestration of CO_2. Our published (and soon to be published) articles provide further details of the theories behind this coupled inversion scheme and its applications (Li & Ito, 2008; Li et al., 2009).

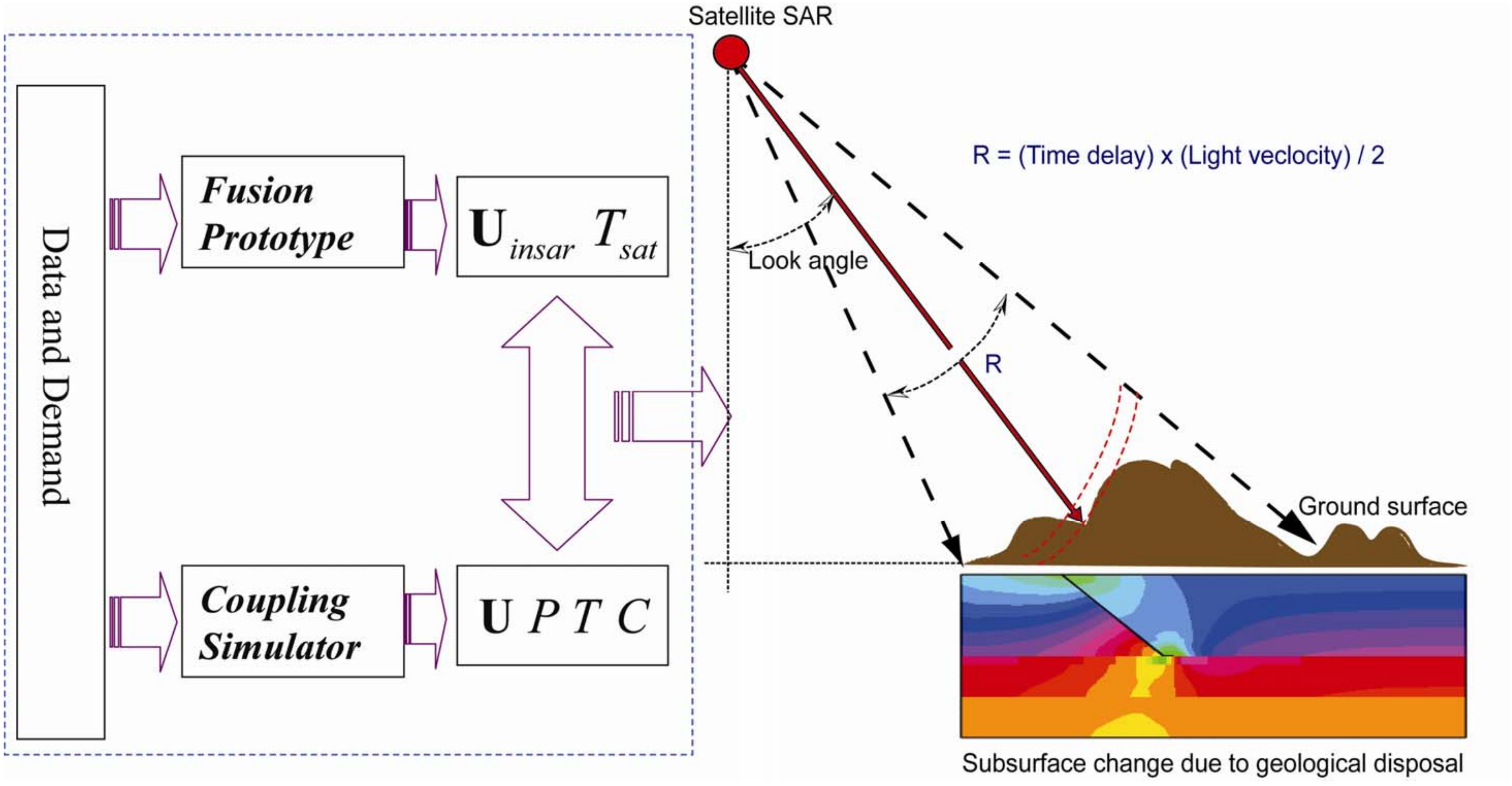

Figure 3. Coupled inversion scheme integrating subsurface characterization with satellite information fusion

3 CONCLUSION

In our research, we have successfully incorporated geosciences with informatics, computer technologies and mathematics. Here, we have described a convergence in approach for coupling modeling and information fusion, and we believe that the birth of this field will greatly advance integration across the spectrum of geoscientific applications. We expect greater cross-discipline interaction to provide fertile ground for advancement in many fields of geoscience. Building on results so far, we want to further demonstrate the importance of multiphysical coupling and information fusion in the field of solar and earth sciences as these techniques are driven by advances in modern information technologies.

4 ACKNOWLEDGEMENTS

QL was partially funded by the Research Institute of Innovative Technology for the Earth (RITE), Japan. The fusion work was partially supported by the project on Research and Development of Remote Sensing Technology for Non-renewable Resources, Ministry of Economy, Trade and Industry (METI), Japan. We would also like to thank Gordon Walker and Hiroaki Toh for their constructive comments, which helped to greatly improve the manuscript.

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