NASA Grant Number NAG5-13269 / UCSD# 22-8825

Budget Justification for Year Three

The budget is primarily committed to salaries of the Principal Investigator and key individuals working on different aspects of the project at Scripps as well as tuition remission for Yang Fan, Graduate Student Researcher. Other significant costs, including the remaining salaries of the staff, will be leveraged against other projects, the existing GPS and seismic arrays projects in southern California, the ongoing funded R&D, and the instrumentation at CSRC, SOPAC, HPWREN, and RoadNet projects. All monthly salary rates are calculated for actual productive time only and include components for employee benefits, provisions for applicable merit increases, and range adjustments in accordance with University of California policy.

Other budget items include IGPP network charges ($225 per man month; no network charges for Research Project Assistant), project specific computing and field supplies ($2,400 or approximately $200 per month), and telephone, toll, mailing and copying expenses ($115 per man month).

In year 3, we will have a subcontract with RBF Consulting, who will work with us to validate and implement the system.

Funds are also requested for travel related to meetings in the County of Riverside and for travel related to fieldwork.

Development of a Real-Time GPS/Seismic Displacement Meter:
Applications to Civilian Infrastructure in Orange and Western Riverside Counties, California
Year Three
04/15/2005 through 04/14/2006

SALARIES & BENEFITS	Rate	# man mo.	Subtotal	Total
Yehuda Bock, Research Geodesist	14,171	0.5	7,086	
Joachim Genrich, Staff Research Associate	6,448	3.33	21,472	
Glenn Offield, Development Engineer	8,874	1	8,874	
George Wadsworth, Programmer Analyst III	7,265	2	14,530	
Yang Fan, Graduate Student Researcher	3,558	4.36	15,511	
Maria Turingan, Research Project Assistant (RPA)	4,495	1	4,495	
Total Salaries	*Man Months = 12.2*		71,968	
Tuition Remission (1 student, Yang Fan)	1,506	9.0	13,554	
Total Salaries & Benefits				85,522

EQUIPMENT

Total Equipment				0

SUPPLIES	Rate	Units	Subtotal	
Network Charges-$225/man mo (no netw charge for RPA)	225	11.2	2,520	
Project specific computing and field supplies- Approx $200 per month			2,400	
Project specific communications: telephones, tolls, mailing, copying- $115/man mo	115	12.2	1,403	
Total Supplies				6,323

SUBCONTRACTS				
RBF Consulting			15,000	
Total Subcontracts				15,000

TRAVEL		Rate	Units	Subtotal	
2 meetings in Riverside (2 people)					
	Mileage	0.485	425	206	
	Per diem	25	4	100	
Fieldwork - Three 2-day trips (2 people)					
	Mileage	0.485	676	328	
	Hotel	120	6	720	
	Per diem	50	12	600	
Total Travel					1,954

TOTAL DIRECT COSTS				108,799

INDIRECT COSTS

	Base	OH Rate	Subtotal	
04/15/2005 - 06/30/2005	19,843	53.5%	10,616	
07/01/2005 - 04/14/2006	75,402	54.0%	40,717	
Base = Total Direct Costs - (Tuition + Equipment)	95,245			
INDIRECT COST TOTAL				51,333

YEAR THREE TOTAL COSTS				160,132

**Development of a Real-Time GPS/Seismic Displacement Meter:
Applications to Civilian Infrastructure in Orange and Western Riverside Counties**

Annual Progress Report (April 15, 2004 – April 14, 2005)

for

**National Aeronautics and Space Administration (NASA)
Grant Number NAG5-13269**

**Prepared by
Yehuda Bock, Principal Investigator**

**Cecil H. and Ida M. Green Institute of Geophysics and Planetary Physics
Scripps Institution of Oceanography
University of California San Diego**

September 23, 2005

Proposal Abstract

We propose a three-year applications project that will develop an Integrated Real-Time GPS/Seismic System and deploy it in Orange and Western Riverside Counties, spanning three major strike-slip faults in southern California (San Andreas, San Jacinto, and Elsinore) and significant populations and civilian infrastructure. The system relying on existing GPS and seismic networks will collect and analyze GPS and seismic data for the purpose of estimating and disseminating real-time positions and total ground displacements (dynamic, as well as static) during all phases of the seismic cycle, from fractions of seconds to years. Besides its intrinsic scientific use as a real-time displacement meter (transducer), the GPS/Seismic System will be a powerful tool for local and state decision makers for risk mitigation, disaster management, and structural monitoring (dams, bridges, and buildings). Furthermore, the GPS/Seismic System will become an integral part of California's spatial referencing and positioning infrastructure, which is complicated by tectonic motion, seismic displacements, and land subsidence. Finally, the GPS/Seismic system will also be applicable to navigation in any environment (land, sea, or air) by combining precise real-time instantaneous GPS positioning with inertial navigation systems. This development will take place under the umbrella of the California Spatial Reference Center, in partnership with local (Counties, Riverside County Flood and Water Conservation District, Metropolitan Water District), state (Caltrans), and Federal agencies (NGS, NASA, USGS), the geophysics community (SCIGN/SCEC2), and the private sector (RBF Consulting). The project will leverage considerable funding, resources, and R&D from SCIGN, CSRC and two NSF-funded IT projects at UCSD and SDSU: RoadNet (Real-Time Observatories, Applications and Data Management Network) and the High Performance Wireless Research and Education Network (HPWREN). These two projects are funded to develop both the wireless networks and the integrated, seamless, and transparent information management system that will deliver seismic, geodetic, oceanographic, hydrological, ecological, and physical data to a variety of end users in real-time in the San Diego region. CSRC is interested in providing users access to real-time, accurate GPS data for a wide variety of applications including RTK surveying/GIS and positioning of moving platforms such as aircraft and emergency vehicles. SCIGN is interested in upgrading sites to high-frequency real-time operations for rapid earthquake response and GPS seismology. The successful outcome of the project will allow the implementation of similar systems elsewhere, particularly in plate boundary zones with significant populations and civilian infrastructure. CSRC would like to deploy the GPS/Seismic System in other parts of California, in particular San Diego, Los Angeles County and the San Francisco Bay Area.

Introduction

At the end year 2 of the project, we have made significant progress towards the goal of a real-time GPS/seismic displacement meter (Figure 1). This annual report summarizes the accomplishments of year 2, of our 3-year project. These include:

(1) Increasing the number of real-time high-rate GPS sites in the targeted four southern California counties (Figure 2), including two sites with seismic/GPS instrument collocation (Camp Elliot and Monument Peak – the former, a USARRAY/PBO location and the latter a long-lived NASA SLR facility).

(2) Decoding the GPS-derived 1 Hz displacements for real-time input to seismic software and other real-time applications.

(3) Creating a Geographic Markup Language (GML) schema for streaming real-time GPS positions, using Open GIS Consortium (OGC) standards.

(4) Analyzing the noise characteristics of very high rate (20-50 Hz) GPS data as a prelude to optimal combination with seismic data.

(5) Developing a web page, and other outreach efforts.
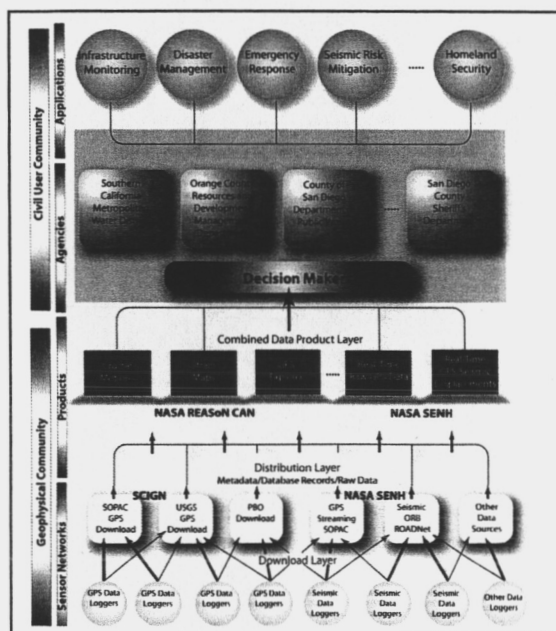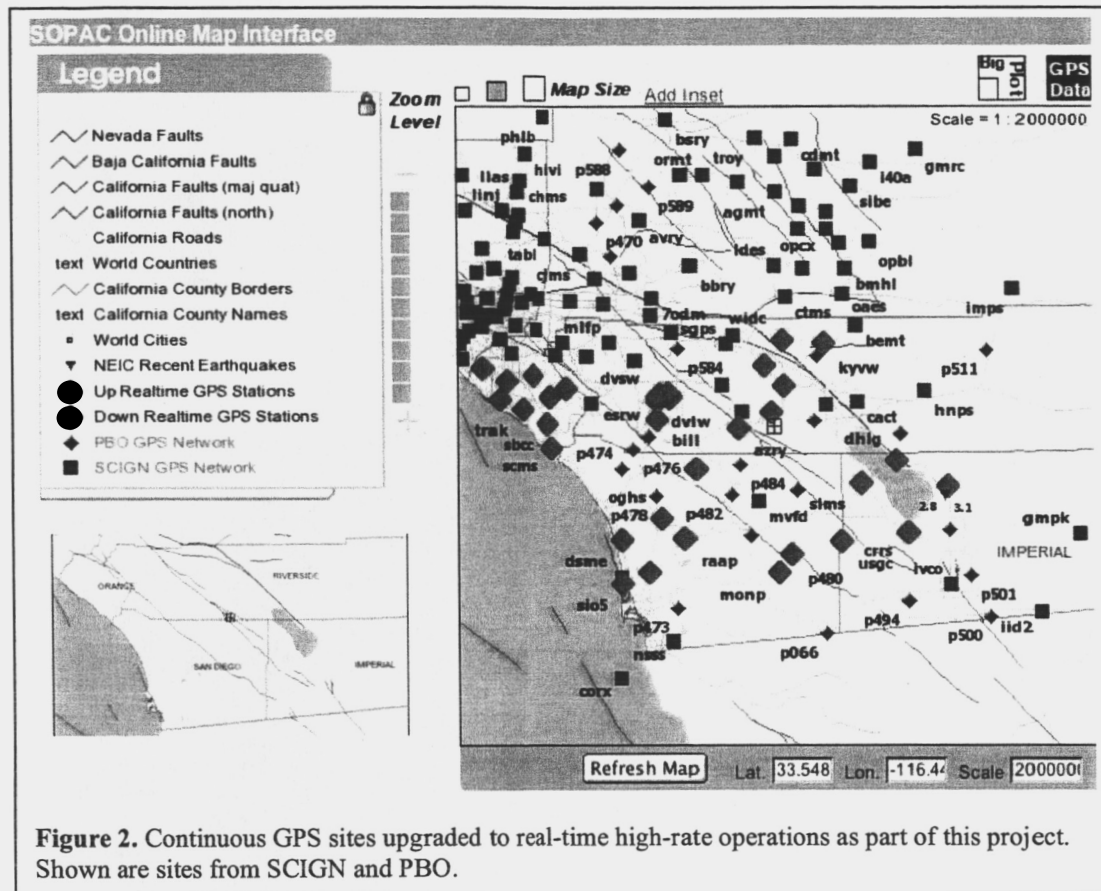

Figure 1. Schematic of our NASA SENH project, and its relation to the NASA REASoN project, GPS Products for the Solid Earth Sciences. The download layer includes GPS and seismic data loggers operated by various projects. Data (real-time, download, and archival modes). and associated metadata are distributed from several sources and merged into a combined data products layer. This (SENH) project focuses on the dissemination of real-time data and data products (e.g., site displacements, earthquake moments, hypocenters) to decision makers in the civil community, in particular to those agencies denoted in the blue boxes. These data can then be assimilated by decision makers for a variety of applications, shown in the orange circles.

Real-Time GPS Sites

The upgrading of continuous GPS (CGPS) sites to real-time operations has been accomplished in collaboration with our civil partners on this project. Not only do these efforts enhance our science objectives and provide significant education and outreach opportunities, but also they directly contribute to the longevity of the scientific networks by generating significant financial resources from users, such as our partners in this project. This is useful in the short-term since our partners bring hard resources to the table (see Table 1), and in the long-term since these sites become an integral part of their infrastructure. We have taken advantage of the long (20-year) history of active, mutually-beneficial collaboration between geophysicists/geodesists and the surveying community in southern California, including field GPS surveys beginning in the mid 1980's and

continuous GPS installations starting in the early 1990's. The establishment of the California Spatial Reference Center (CSRC – http://csrc.ucsd.edu/) in 1999 has enhanced and formalized this relationship. The goal of the CSRC is to use the GPS science infrastructure as a backbone for the establishment and long-term maintenance of a spatial reference system for California, as the legal basis for positioning (horizontal and vertical and their temporal changes). Currently, CSRC and its partners (e.g., Caltrans, MWD, and southern California Counties) are assisting the Plate Boundary Observatory (PBO) in locating and permitting new stations.

Figure 2. Continuous GPS sites upgraded to real-time high-rate operations as part of this project. Shown are sites from SCIGN and PBO.

Since 2001, the collaboration between geophysicists/geodesists and the surveying community, represented by counties, local governments, agencies, and private entities, has focused on upgrading continuous GPS (CGPS) sites from routine periodic (3-24 hour) downloads of 15-30 s sampled data, to streaming high-rate (1 Hz or higher) data in real-time (<1 s latency). These efforts were initiated after the 1999 Hector Mine earthquake when (30 s) SCIGN data were analyzed using the method of instantaneous positioning (*Bock et al.*, 2000) to directly measure seismic motions and Los Angeles basin resonance effects (*Nikolaidis et al.*, 2001). On the other hand, surveyors are interested in continuous access to high-rate data to support real time kinematic surveys (*Andrew*, 2003), and photogrammetric and LIDAR airborne surveys.

The first effort was the Orange County Real Time Network (OCRTN), a collaboration of Orange County, CSRC, and SCIGN, which captured teleseismic waves from the 3

November, 2002 Mw Denali 7.9 Denali fault earthquake (*Bock et al.*, 2004). Next, USGS Menlo Park, SCIGN, and UC Berkeley collaborated to upgrade 14 BARD and SCIGN sites in the Parkfield area (*Langbein and Bock*, 2004), and the capturing of two large earthquakes: the 22 December 2003, Mw 6.5 San Simeon earthquake (*Hardebeck et al.*, 2004; *Ji et al.*, 2004) and the long-anticipated 28 September 2004 Mw 6.0 Parkfield earthquake (*Langbein et al.*, 2004) (Figure 3).
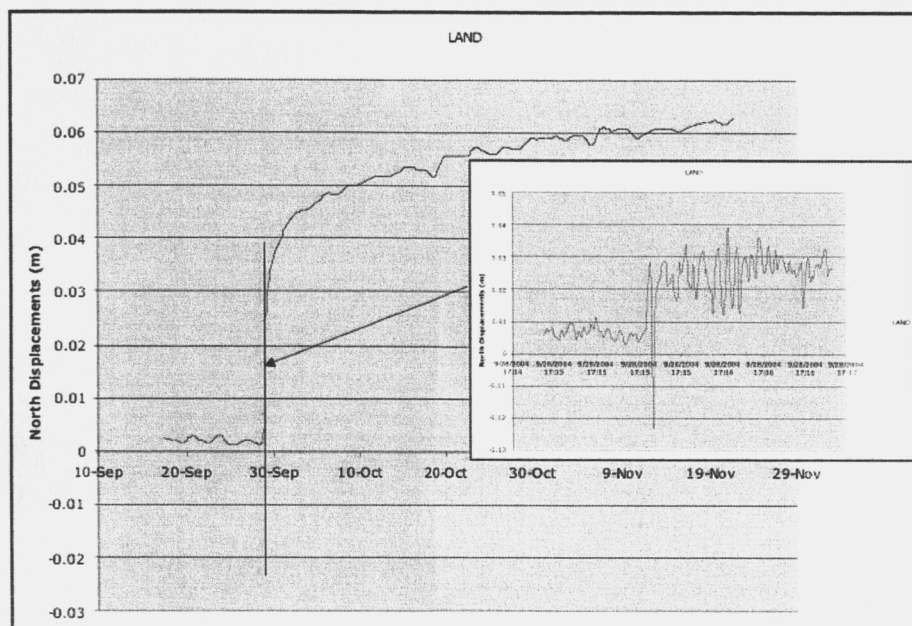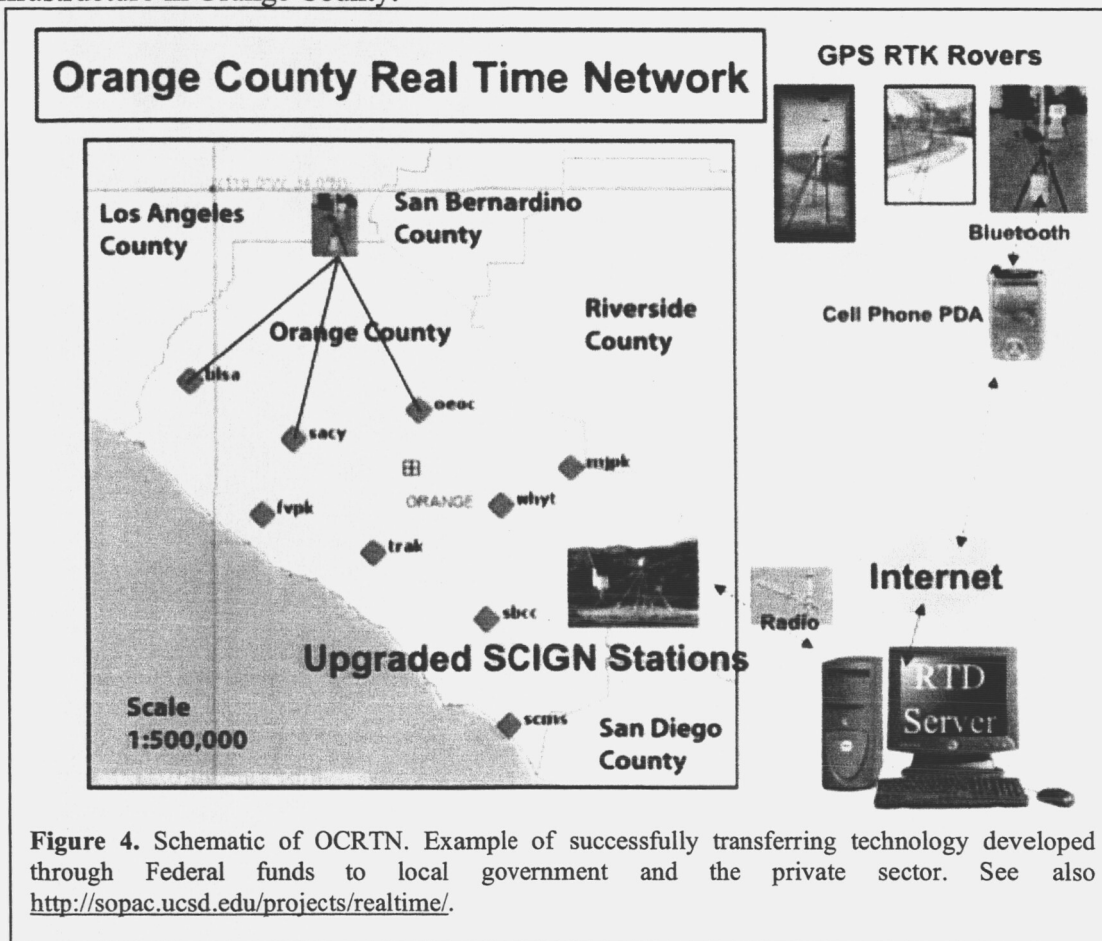

Figure 3. 1 Hz Position Time Series for the 2004 Parkfield Earthquake. Shown are north displacements (m) of station LAND including preseismic, dynamics, coseismic, and postseismic displacements, computed from 1 Hz data from upgraded SCIGN stations.

Entity	Amount	Project
CSRC (NOAA funds)	$350,000	Orange County Real Time Network
NASA SENH (this project)	$407,000	Orange & Riverside Real Time Networks
Orange County PFRD	$183,500	Orange County Real Time Network
Riverside County DOT	$10,000	Riverside County Real Time Network
Riverside County Flood and Water Conservation District	$25,000	Riverside County Real Time Network
San Diego Dept. of Public Works	$450,000	San Diego County Real Time Network
Metropolitan Water District	$70,000	Riverside County Real Time Network

Table 1. Resources from Federal grants (NASA/NOAA) and local partners that have been provided in direct support of real-time high-rate CGPS (Figure 2), and applications.

Orange County

The 9 operational sites are part of the Orange County Real Time Network (OCRTN – Figure 4) established in 2001-2002, in collaboration with the County of Orange Resources and Development Management Department (http://www.ocrdmd.com/). RDMD serves all of Orange County by providing flood control, water quality enhancement, recreation, agricultural, and public works services. Their interests in the project include precise real-time geospatial information for decision makers, inundation maps and evacuation procedures resulting from natural hazards (earthquakes, landslides, tsunamis) and infrastructure failure (transportation, levees, dams). One of the primary users of OCRTN is Caltrans District 12, responsible for the state's transportation infrastructure in Orange County.
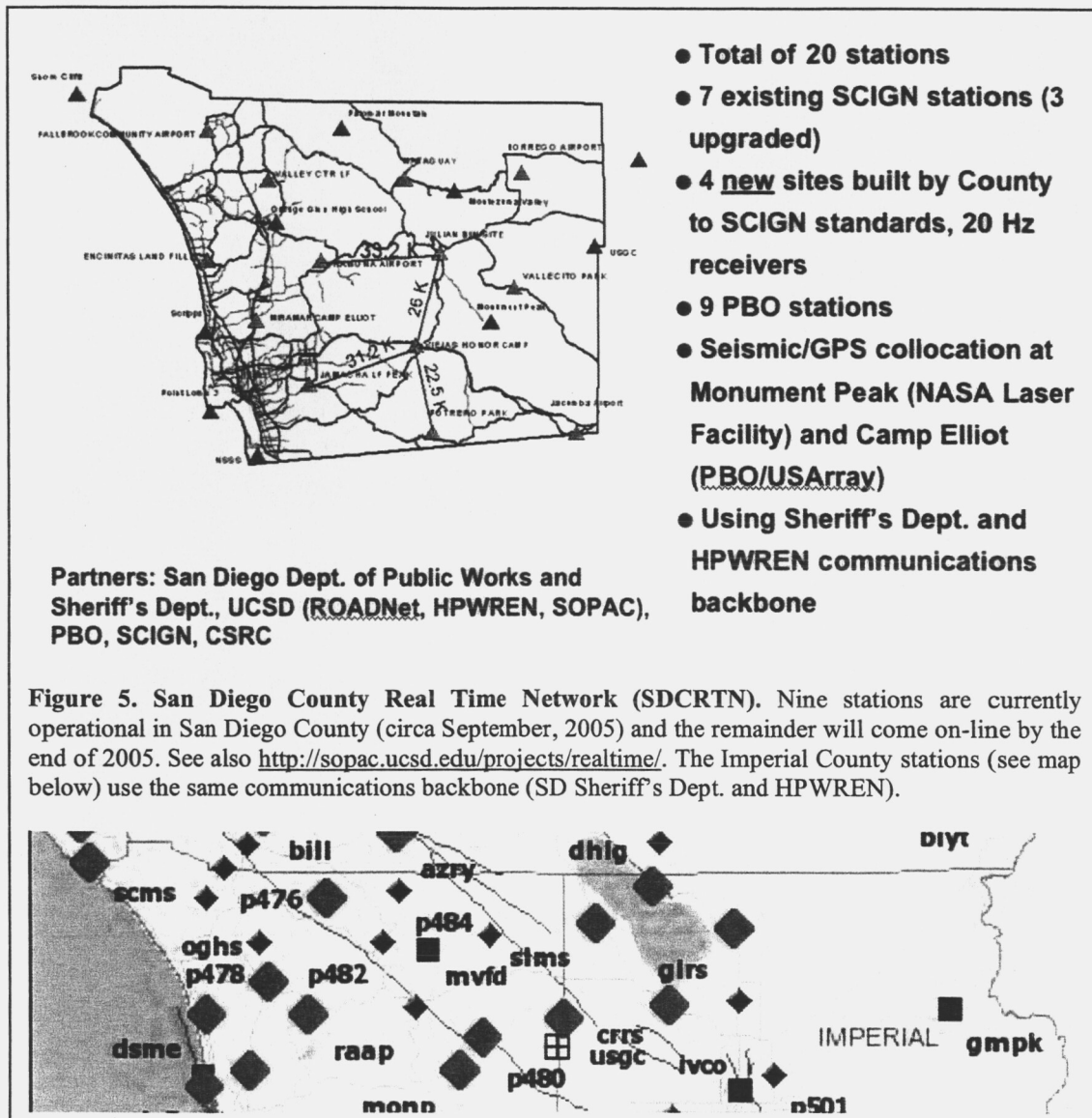

Figure 4. Schematic of OCRTN. Example of successfully transferring technology developed through Federal funds to local government and the private sector. See also http://sopac.ucsd.edu/projects/realtime/.

San Diego and Imperial Counties

We are currently working with our San Diego partners (see below), the Plate Boundary Observatory (PBO), and UNAVCO's NUCLEUS project, on the CGPS upgrades in San Diego and Imperial Counties (Figures 5-6).
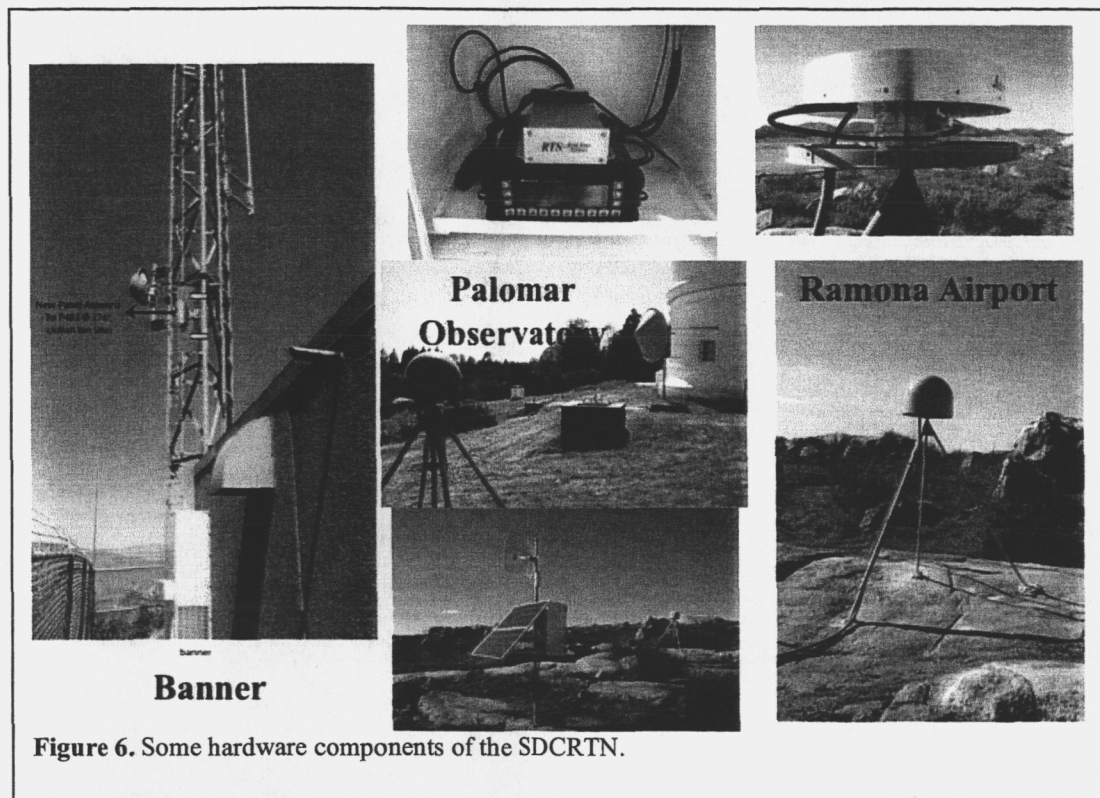
County of San Diego Department of Public Works (http://www.co.san-diego.ca.us/dpw/) — public responsibilities in the areas of land development, environment, transportation and engineering in San Diego County. The decision support tools will provide precise real-time positioning and displacements support for (natural hazards) disaster management in the areas of transportation and engineering

infrastructure. We will also work closely with Caltrans District 11, responsible for the state's transportation infrastructure in San Diego and Imperial Counties.

San Diego County Sheriffs Department (http://www.sdsheriff.net/home/) — chief law enforcement agency in the County of San Diego. The department is comprised of approximately 4,000 employees, including sworn officers and professional support staff. The department provides general law enforcement and emergency services for the people of San Diego County in a service area of approximately 4,200 square miles. The decision support tools will provide precise real-time positioning/navigation support for emergency response (homeland security related), (natural hazards) disaster management, precise mapping of crime scene investigations, and fleet management.


- Total of 20 stations
- 7 existing SCIGN stations (3 upgraded)
- 4 **new** sites built by County to SCIGN standards, 20 Hz receivers
- 9 PBO stations
- Seismic/GPS collocation at Monument Peak (NASA Laser Facility) and Camp Elliot (PBO/USArray)
- Using Sheriff's Dept. and HPWREN communications backbone

Partners: San Diego Dept. of Public Works and Sheriff's Dept., UCSD (ROADNet, HPWREN, SOPAC), PBO, SCIGN, CSRC

Figure 5. San Diego County Real Time Network (SDCRTN). Nine stations are currently operational in San Diego County (circa September, 2005) and the remainder will come on-line by the end of 2005. See also http://sopac.ucsd.edu/projects/realtime/. The Imperial County stations (see map below) use the same communications backbone (SD Sheriff's Dept. and HPWREN).

Figure 6. Some hardware components of the SDCRTN.

Riverside County

Efforts in Riverside County have shifted from the Department of Transportation and Flood Control and Water Conservation District to MWD (see description below).

Metropolitan Water District of Southern California (http://www.mwdh2o.com/) — MWD is a consortium of 26 cities and water districts that provides drinking water to nearly 18 million people in parts of Los Angeles, Orange, San Diego, Riverside, San Bernardino and Ventura counties. Metropolitan currently delivers an average of 1.7 billion gallons of water per day to a 5,200-square-mile service area. The decision support tools from this project will provide precise real-time positioning/displacements support for emergency response, (natural hazards) disaster management, and infrastructure monitoring. We are currently working with this partner on the Riverside County Real Time Network (Figure 7, including reference stations used for dam monitoring at Diamond Valley Lake (Figure 8.
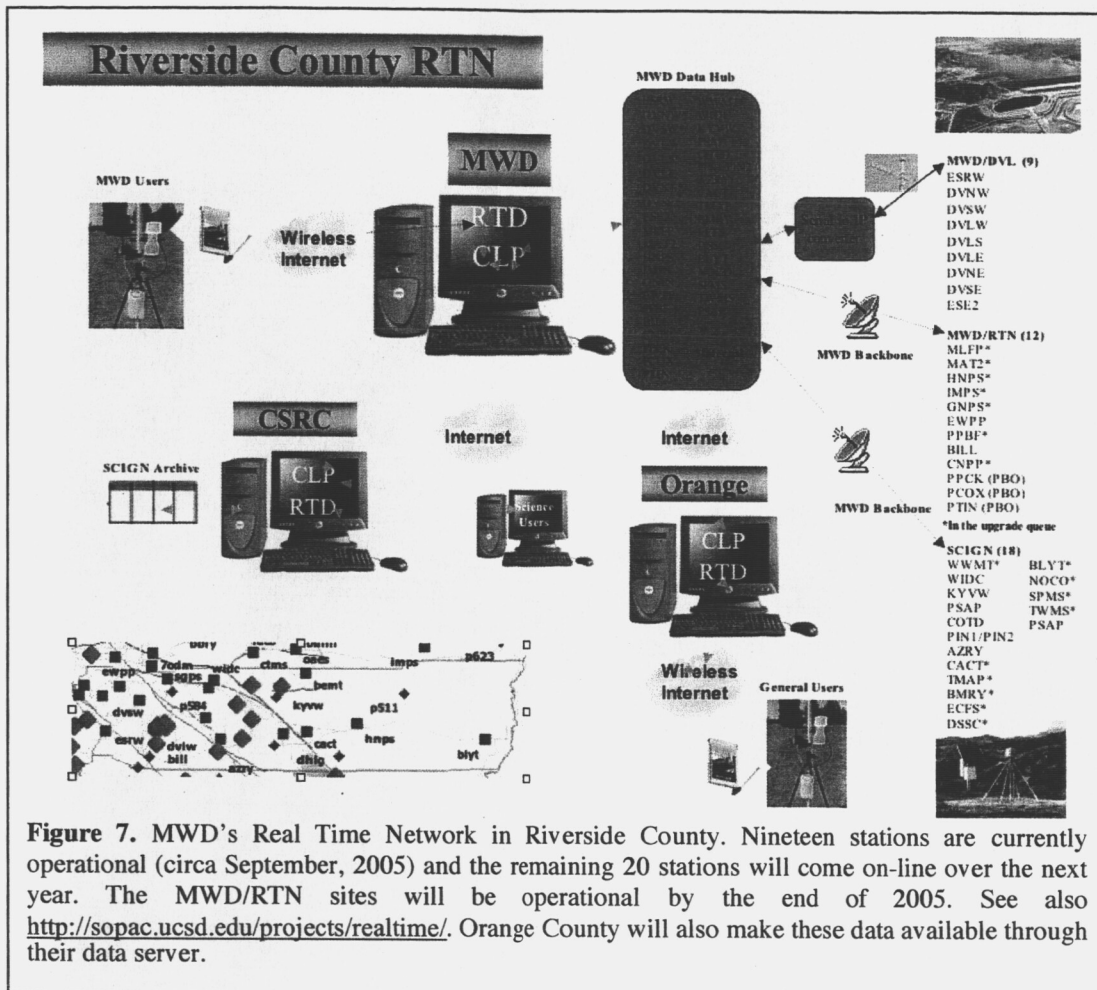
Figure 7. MWD's Real Time Network in Riverside County. Nineteen stations are currently operational (circa September, 2005) and the remaining 20 stations will come on-line over the next year. The MWD/RTN sites will be operational by the end of 2005. See also http://sopac.ucsd.edu/projects/realtime/. Orange County will also make these data available through their data server.

Figure 8. MWD's Diamond Valley Lake. This reservoir contains a 6-month emergency water supply for southern California, and lies between two active geologic faults (San Jacinto and Elsinore). There are 9 1 Hz GPS stations monitoring three earthen dams.

Real-Time Position Server

We have decoded the real-time position output by the RTD Pro server in open Geodetics RYO binary format, for input to the Antelope seismic software and to the Narada broker developed by University of Indiana.

Seismic Software

The real-time seismic/GPS displacement meter requires the merging of GPS positions with traditional seismic data streams. As a critical step in this development, we have written a new data acquisition program, ryo2orb, which acquires near-real-time Global Positioning System (GPS) data from an RTD Pro data server in Geodetics RYO format and places them on an Antelope orbserver (*Lindquist et al.*, 2005) (Figures 9-10). Once on an orbserver these geodetic data may be saved as time-series (usually in SEED format) in a Datascope database of css3.0-compatible schema, alongside the continuous data from a seismic network.. In order to help manage the total packet transmission rates, the ryo2orb module allows optional time concatenation of contiguous samples and/or multiplexing of stations from a given network. This module promises to significantly simplify the routine analysis of side-by-side geodetic and seismic data from large earthquakes.
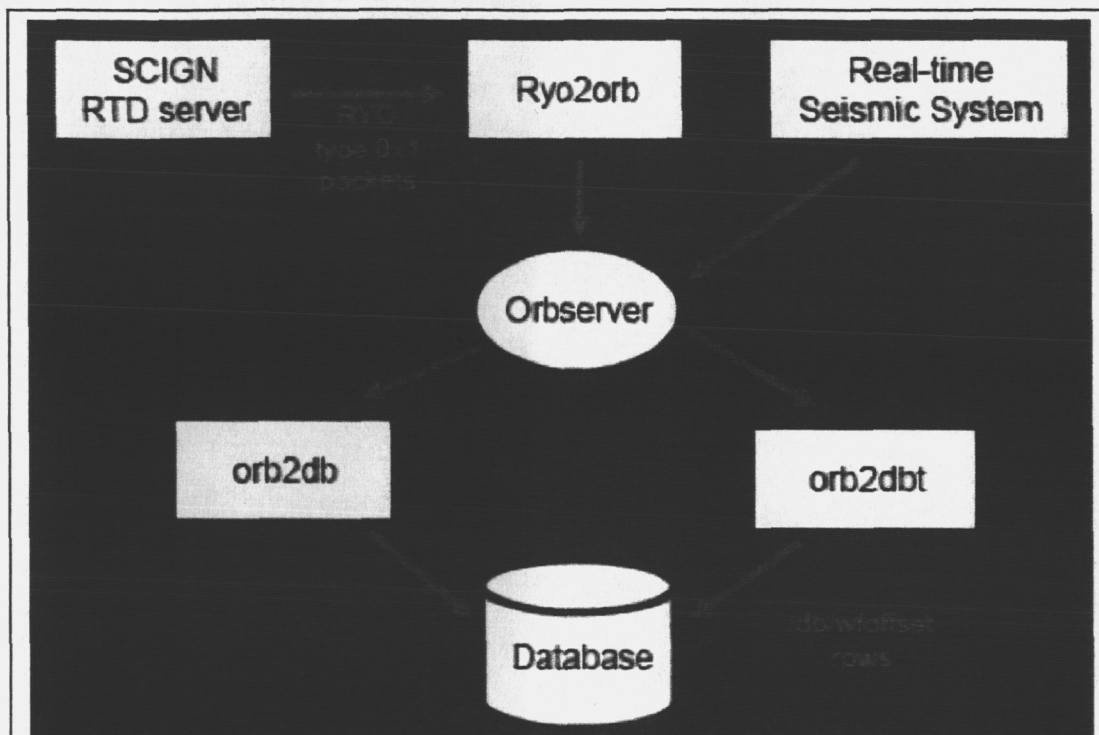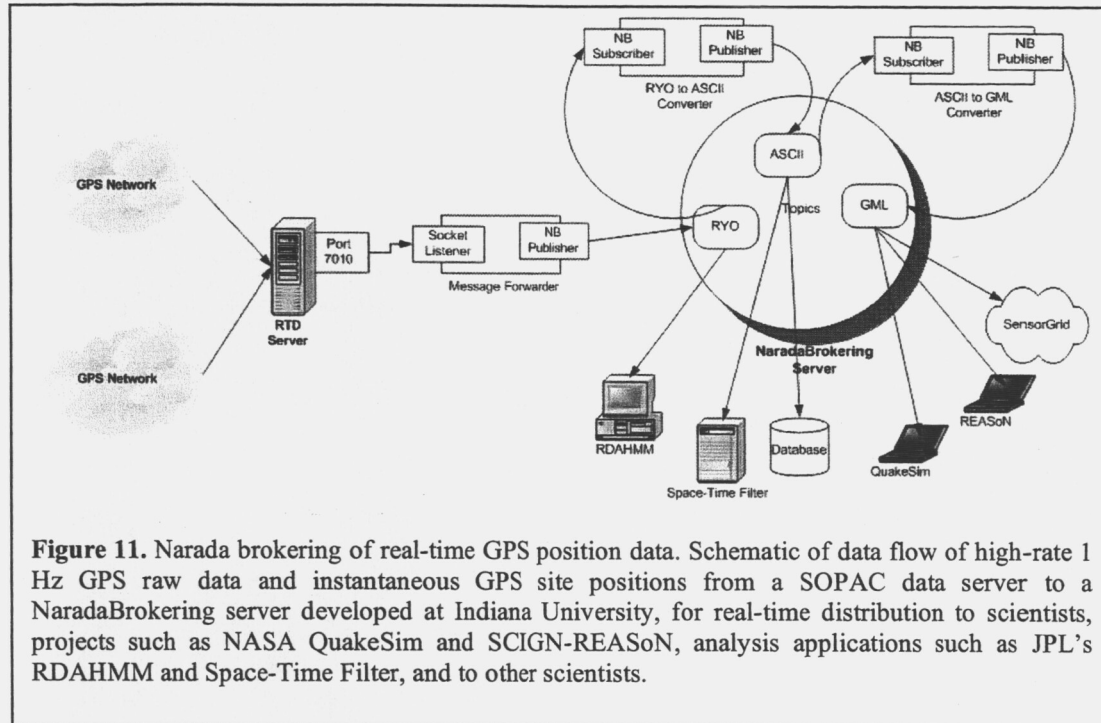
Figure 9. Flow of GPS Positions into Seismic Software. The diagram shows the various features of the ryo2orb acquisition program, in the context of an Antelope seismic acquisition and processing system. The ryo2orb program emits both MGENC packets of repackaged time-series data, and /db/wfoffset database rows with the absolute offsets of the time-series.
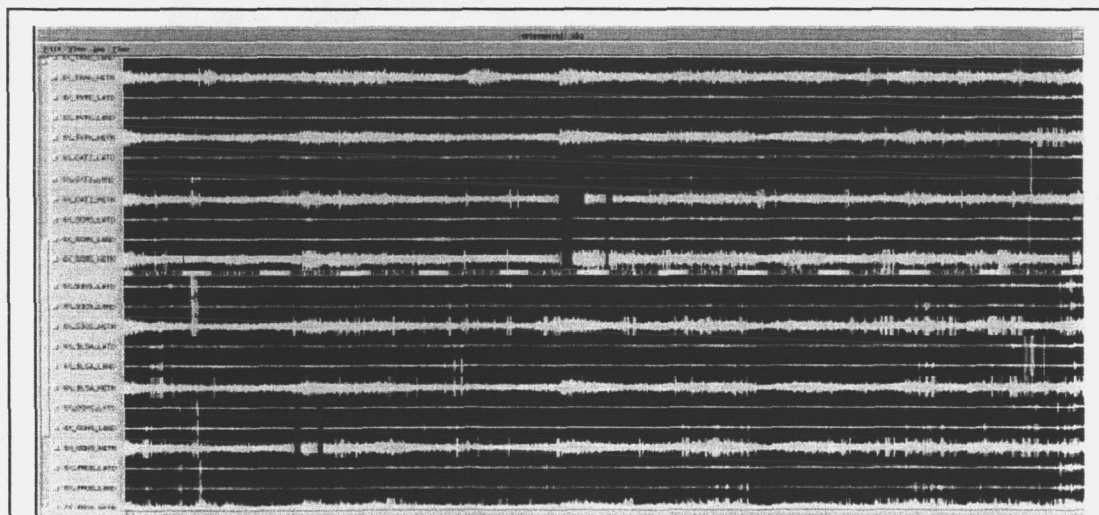
Figure 10. GPS position time series as displayed in scrolling real-time display by the Antelope orbmonrtd program. These data are also available in an interactive database with the Antelope dbpick command.

Narada Broker

The Narada broker (Figure 11) allows us to stream GPS positions in RYO format from the RTD Pro server to users. This system is now operational and streaming RYO data, flat files, and GML format (see below) from the upgraded CGPS stations.

Figure 11. Narada brokering of real-time GPS position data. Schematic of data flow of high-rate 1 Hz GPS raw data and instantaneous GPS site positions from a SOPAC data server to a NaradaBrokering server developed at Indiana University, for real-time distribution to scientists, projects such as NASA QuakeSim and SCIGN-REASoN, analysis applications such as JPL's RDAHMM and Space-Time Filter, and to other scientists.
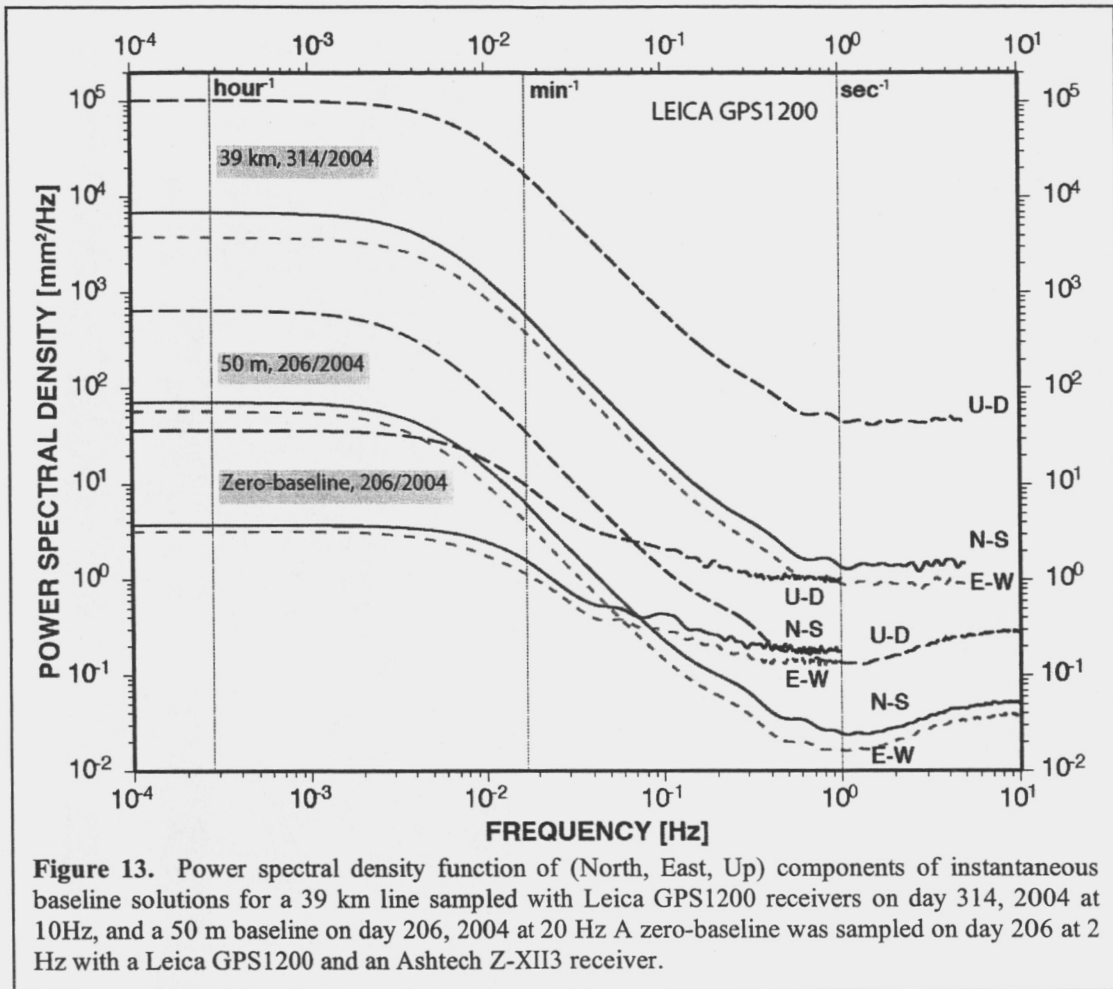
The GML Observation Schema for SOPAC position messages and the data binding implementation for this schema have been developed by Galip Aydin at University of Indiana. The schema is based on OGC's (Open GIS Consortium) enhanced Observations & Measurements specification. The element that contains the details about an individual station is <sopac:PositionMessage>. A <sopac:ObservationCollection> element may contain multiple station positions. Thus a GML instance for an RYO message would have a <sopac:ObservationCollection> which contains multiple <sopac:PositionMessage> elements. The latest version of the schema is sopacGPS.xsd and it is located at <http://www.crisisgrid.org/schemas/om/>http://www.crisisgrid.org/schemas/om/. There are also two sample instances in the same directory, PositionMessage.xml and SOPAC-Positions.xml to further demonstrate the idea of a single position message and a collection of positions. We used Apache XMLBeans (<http://xmlbeans.apache.org/>http://xmlbeans.apache.org/) for data binding. Also, we wrote another application which reads the ASCII position messages from a Narada Brokering topic and after converting to GML publishes to another topic. Thus, we can provide streaming access to positions in GML along with RYO and text formats via Narada Brokering.
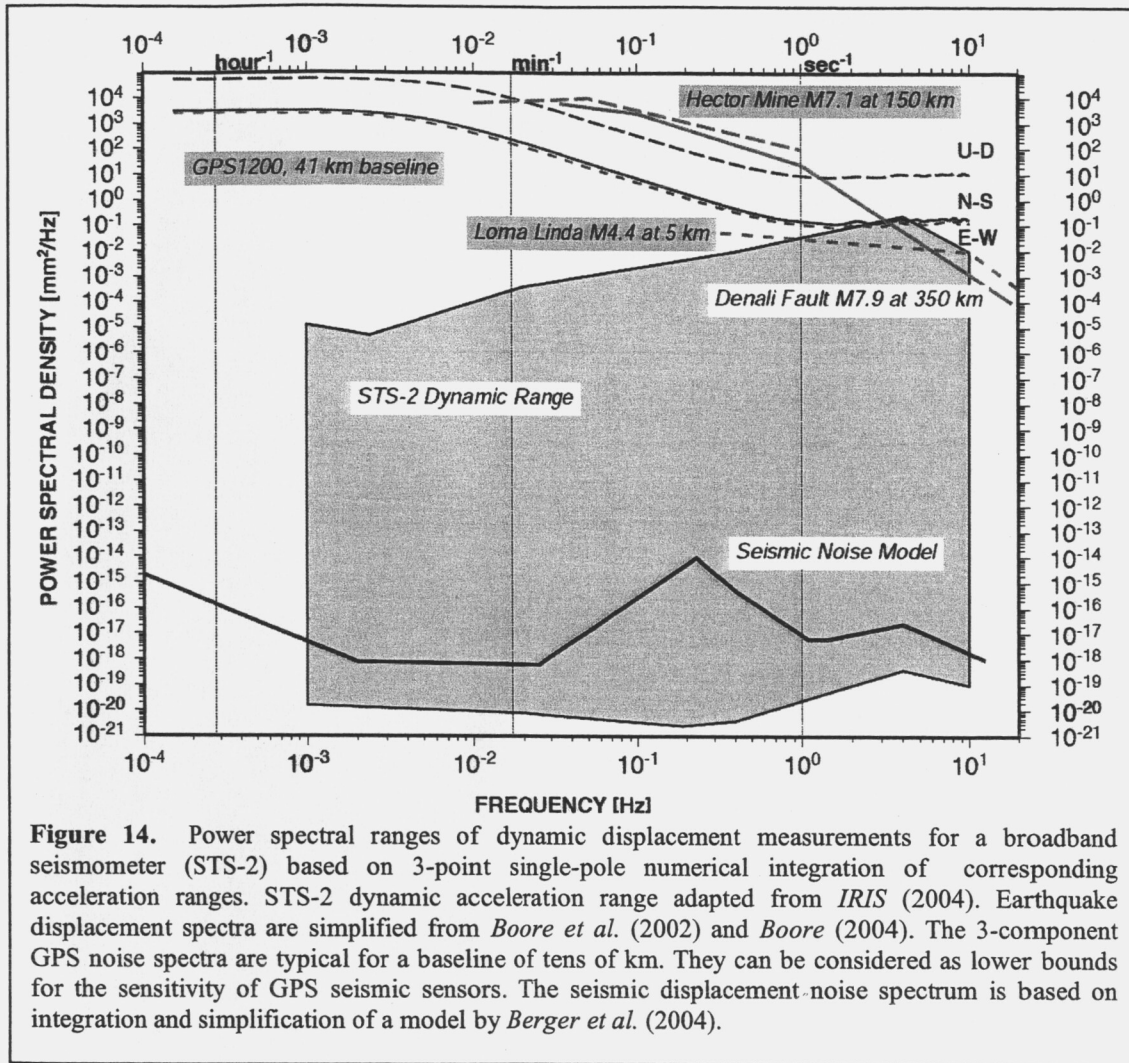
Noise characteristics of very high rate GPS data

As a prelude to combination of GPS displacements with seismic measurements, we investigated the noise characteristics of very high rate GPS positions (*Genrich and Bock*, 2005). We measured 7 baselines during time intervals void of detectable transient signals at sampling rates of 1-50 Hz with geodetic receivers from 4 manufacturers (Figure12). Our tests over short distances (meters) to typical SCIGN station spacing (10's of km) show no loss of spatial resolution compared to 1 Hz samples. Measurement noise is red with the typical ramp profile of log-log spectra below about 0.5 Hz. Above this frequency, noise is essentially white. Low-pass filtering of high rate positions achieves improved spatial resolution compared to decimated raw samples. Averaging 20 Hz measurements to 2 Hz samples on a 40 km baseline (Figure 13), for example, yields about 0.5 mm horizontal and about 3-4 mm in vertical accuracy at high frequencies. These accuracies are a factor of 2-2.5 better than for 2 Hz raw samples. The improvements in spatial resolution due to averaging at high frequencies are substantial, and approach the theoretical "square-root-of-n" expectation for independent samples. However, since noise spectral densities rise rapidly below about 0.5 Hz, low-pass filtering is only effective above this frequency. These results have important implications for the design of continuous GPS (CGPS) networks for crustal deformation and structural monitoring, and for positioning and attitude determination of dynamic platforms. Also, they show the compatibility of high-rate GPS displacements with traditional seismic measurements (Figure 14)
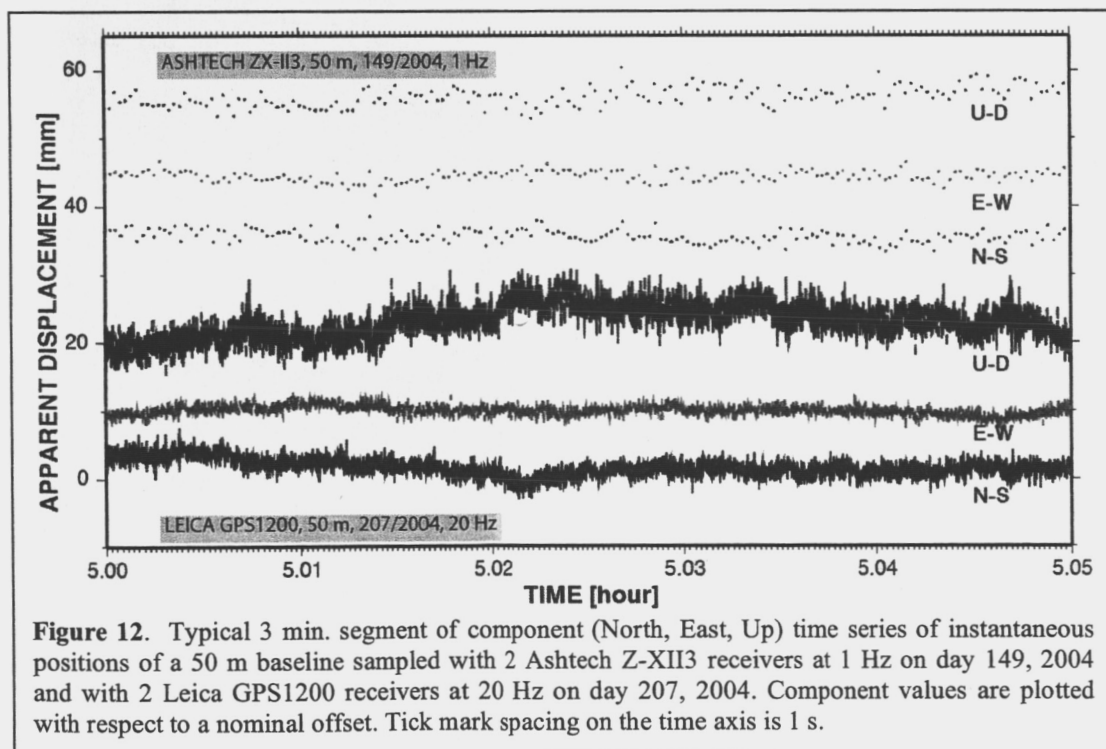
Figure 12. Typical 3 min. segment of component (North, East, Up) time series of instantaneous positions of a 50 m baseline sampled with 2 Ashtech Z-XII3 receivers at 1 Hz on day 149, 2004 and with 2 Leica GPS1200 receivers at 20 Hz on day 207, 2004. Component values are plotted with respect to a nominal offset. Tick mark spacing on the time axis is 1 s.

Figure 13. Power spectral density function of (North, East, Up) components of instantaneous baseline solutions for a 39 km line sampled with Leica GPS1200 receivers on day 314, 2004 at 10Hz, and a 50 m baseline on day 206, 2004 at 20 Hz A zero-baseline was sampled on day 206 at 2 Hz with a Leica GPS1200 and an Ashtech Z-XII3 receiver.

Figure 14. Power spectral ranges of dynamic displacement measurements for a broadband seismometer (STS-2) based on 3-point single-pole numerical integration of corresponding acceleration ranges. STS-2 dynamic acceleration range adapted from *IRIS* (2004). Earthquake displacement spectra are simplified from *Boore et al.* (2002) and *Boore* (2004). The 3-component GPS noise spectra are typical for a baseline of tens of km. They can be considered as lower bounds for the sensitivity of GPS seismic sensors. The seismic displacement noise spectrum is based on integration and simplification of a model by *Berger et al.* (2004).

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Web Site

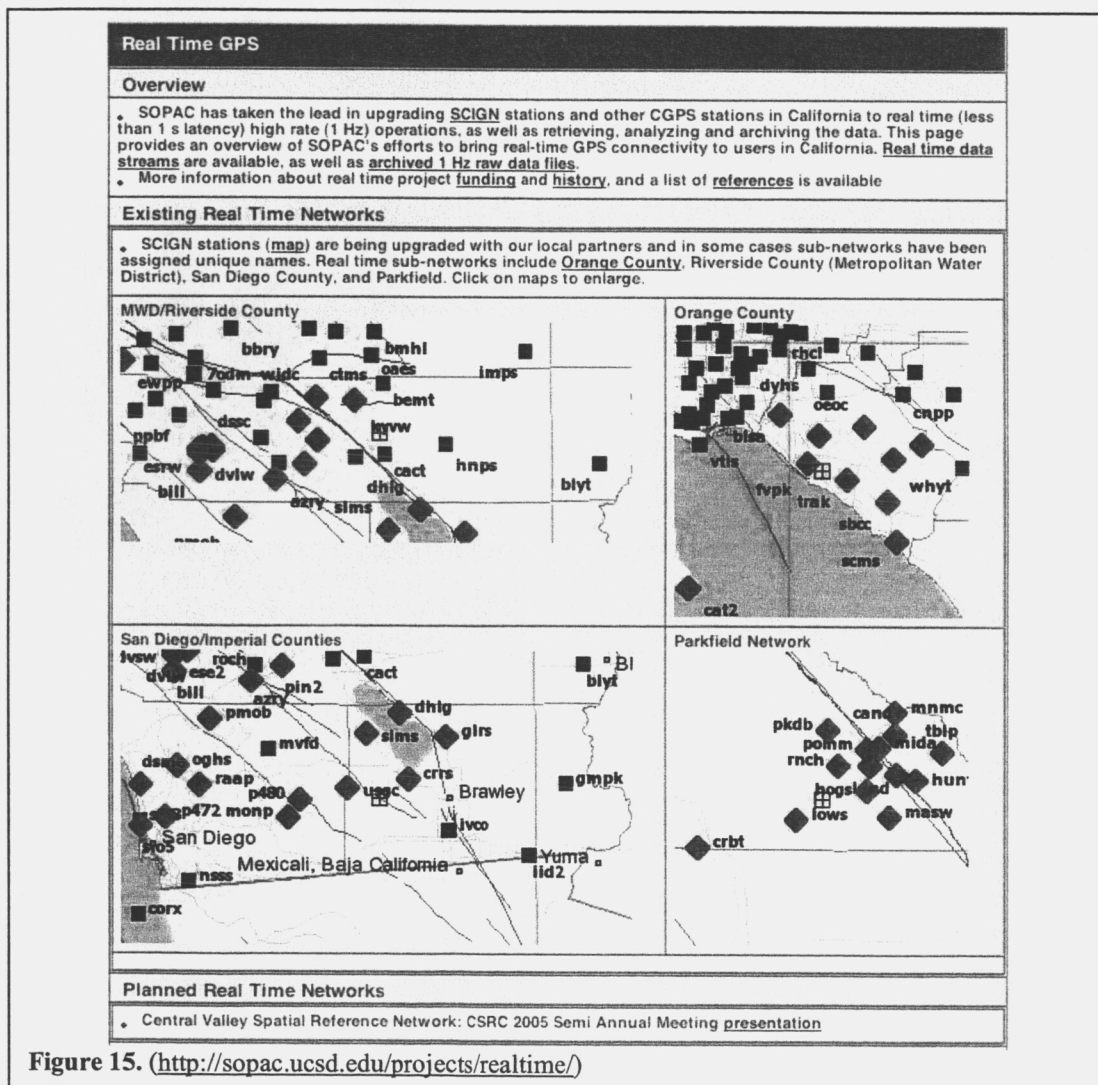We have created a web page as part of the SOPAC web site (Figure 15).

Figure 15. (http://sopac.ucsd.edu/projects/realtime/)