Summary of Large N Workshop
Seattle, Washington
May 24, 2012

Meeting Report for the IRIS BoD

- Rationale for meeting:
  - The plans presented in the IRIS 2013-18 proposal will include a commitment to sustaining the existing PASSCAL and USArray/FA pools (broadband, Texan and multichannel) and tracking and incorporating new developments that emerge from the commercial sector, especially in new broadband sensors. This small workshop, with a select group of invitees from the broader community, specifically explored the science needs and goals for "Large N" experiments. New instrumentation discussions focused on new and innovative technologies to support the "Large N" deployment concept, which will complement the current broadband and Texan capabilities.

- Attendees
  - Seth Moran smoran@usgs.gov - PASC/USGS
  - James Gridley james.gridley@iris.edu - IRIS
  - Kent Anderson kent@iris.edu - IRIS
  - Bob Woodward woodward@iris.edu - IRIS
  - Michael West west@gi.alaska.edu - PASC/UAF
  - Jesse Lawrence jflawrence@stanford.edu - PASC/Stanford
  - Shad O'Neel soneel@usgs.gov - PASC/USGS
  - Lee Liberty lml@cgiss.boisestate.edu - PASC/Boise State
  - Tim Parker tparker@passcal.nmt.edu – PIC/NMT
  - Rick Aster aster@nmt.edu - PIC/NMT
  - John Hole hole@vt.edu - BOD/VT
  - Paul Davis pdavis@ess.ucla.edu - BOD/UCLA
  - Sridhar Anandakrishnan sak@essc.psu.edu - Penn State
  - Frank Vernon flvernon@ucsd.edu - UCSD
  - Chris Hayward hayward@smu.edu - SMU
  - Jonathan Lees jonathan.lees@unc.edu - UNC
  - David Okaya okaya@usc.edu - USC
  - Charles Langston clangstn@memphis.edu - CERI Memphis
  - Doug Toomey drt@uoregon.edu - UO
  - John Vidale vidale@ess.washington.edu - U Washington (UW)
  - Ken Creager kcc@ess.washington.edu - UW
  - Steve Malone steve@ess.washington.edu - UW
  - Ken Dueker Dueker@uwyo.edu – U Wyoming
  - Robert Mellors mellors1@llnl.gov - LLNL
  - Larry Douglas Brown ldb7@cornell.edu - Cornell (via phone)
  - Chuck Ammon cja12@psu.edu - Penn State (via phone)
  - Cindy Ebinger cebinger@ur.rochester.edu - PASC/Rochester (via phone)
  - Last-minute cancellations: Paul Winberry (Central Washington), Alan Levander (Rice)

- Agenda
  - 8:30 Introductions and Welcome (Moran)
  - 8:45 The big picture; the 2013-2018 proposal and the future of the IRIS Portable program (Woodward)
  - 9:00 Trade study: how feasible is "Large N", what is out there and how much would it cost? (Parker)
  - 9:15 View from the Board (Hole)
  - 9:30 Array of Arrays (Ammon)
  - 9:45 5-minute presentations with 5 minutes of discussion
  - 10:25 Break
  - 10:40 5-minute presentations, continued
  - 12:30 Lunch
  - 1:30 5-minute presentations, continued
  - 2:50 Break
  - 3:10 Summary of themes from 5-minute presentations, open discussion for next directions
  - 5:00 Adjourn

- Summary of meeting
  - 5-minute talk titles & authors
    - Larry Brown: Dense array recording
    - Jonathan Lees: Large N array - Volcano Seismic Real-time Imaging
    - Rick Aster: Seismic Interferometry at Erebus via Large N
    - Sridhar Anandakrishnan: GeoPebbles
    - Chuck Langston: Continuum Seismic Recording and Wave Gradiometry
    - Ken Creager: Insights into tectonic tremor using arrays
    - Rob Mellors: Array studies
    - John Vidale: Bang for the buck of "Uses for arrays of arrays"
    - Ken Dueker: What do you get when you increase N by factor of 4?
    - Doug Toomey: Imaging magmatic systems in the ocean
    - David Okaya: Large N Portable arrays for crustal seismic anisotropy
    - Jesse Lawrence: "Large N": A Split Personaility: (Strong-motion to broadband)
    - Frank Vernon: Array studies of microseismicty at the San Jacinto Fault Zone
    - Lee Liberty: High-resolution seismic imaging of the near-surface
    - Paul Davis: Large-N RAMP
    - Shad O'Neal: Getting to "N" in harsh climates
    - Mike West: The case for N = 1-10

  - General themes:
    - Imaging of structure:
      - Resolution has been fundamentally limited by the size of N. Imaging experiments clearly would benefit from Large N at multiple scales ranging from mantle anisotropy to whole-crust structure to mapping of near-surface faults and hydrologic features. Examples were shown of the improvement in resolution of, for example, images of crustal anisotropy with Large N, and also the reduction in spurious features in crustal images achieved by increasing station density by a factor of 4.
      - Solutions exist for achieving Large N imaging at high frequencies (> 1 Hz), particularly in geophysical exploration via evolving technologies such as "Land

Streamers". However, there currently is no viable means for the academic community to achieve Large N at lower frequencies (> 5 s??). Some discussion also focused on 4-D imaging of structural changes over time, particularly as regards to volcano imaging and fault-zone studies. Such studies ultimately have potential for hazards mitigation, but real-time telemetry and data processing systems for handling data flow from real-time Large N networks would be required in order to enable such a capability.

- Source studies:
    - Studies of seismic sources have benefited greatly from recent attempts to deploy larger numbers of stations. The "Array of Arrays" project showed that with a few arrays of "small N" (~20 sensors per array), detection and mapping of time-variable ETS tremor that is composed of small low-frequency earthquakes is possible via back-projection techniques and other array processing methods. Studies of persistent seismicity clusters such as the San Jacinto Fault Zone show that closely-space earthquakes have large variations in focal mechanisms, and raise questions about how the structure of faults evolve with time. RAMP responses to large earthquakes have to date been limited by the size of "N" and logistical hurdles, but where deployed have greatly enhanced ability to trace aftershock progression, something that is potentially critical for hazards mitigation as illustrated by the recent Christchurch earthquakes that demonstrated that aftershocks can be predictive of where the next aftershock is most likely occur. Finally, studies of "exotic" sources produced by volcanoes (tremor, explosions, rockfalls) and glaciers (calving, avalanches, basal-slip seismicity) have produced some science that has truly been transformational (i.e., the recent discovery that calving-induced seismicity is produced not during the calving event itself, but rather in association with subsequent iceberg impact with water).
    - "Large N" requirements include robust and quickly-deployable instrumentation that potentially can be left at a site for up to a year without visitation. Telemetry is a must for any hazard-mitigation-based deployment such as RAMP, although not every sensor and/or every bit of information would need to be telemetered (i.e., a system could be implemented to transmit low-bandwidth derived data products, such as body-wave arrivals and peak-amplitude info, to reduce bandwidth, while recording full wave-forms on-site for subsequent analysis). For near-field source studies it is important to stay on scale for a wide-range of ground motions (say, M=0 to M=5), which is achieved currently through operation of weak- and strong-motion sensors at a common site. In addition, recording at > 100 Hz is important for studying details of rupture properties in the near-field, particularly for small events where the source corner frequency is high.

- Ability to work in challenging environments:
    - There are a range of "new" environments, including temperate glaciers, volcanoes, remote areas such as the Aleutians, and designated Wilderness areas as well as National Parks, which, because of severe logistical challenges, have been understudied. A range of basic scientific questions, including the impact of sea-level rise on calving glacier systems, the relationship between repeating events and stick-slip behavior along glacier-rock interfaces, how active fault systems evolve over short time scales, and whether temporal changes in magmatic systems can be

detected in real-time, require robust and easy-to-deploy seismic instrumentation to address. Logistical challenges such as limited and/or expensive and/or hazardous access, difficult permitting, significant snow/rainfall, and rapid movement and/or melting of glacier snow and ice have all severely restricted the types of experiments done to date. In such environments, getting to "N" has sometimes been the issue rather than getting to "Large N". However, studies that have succeeded in getting to "N" in these environments have also produced transformative science.

- Several examples of moderate-to-Large N deployments in remote/harsh climates, including an imaging experiment at Erebus that produced fascinating detailed images of the shallow magma conduit system and an experiment on Reventador volcano in Ecuador that is targeted towards deploying ~500 sensors for 4-D imaging, illustrated the potential for new discoveries if Large N can be implemented in such environments.
- The hope is that in the process of developing a Large N capability, associated development of robust, lightweight, and low-power instrumentation and packaging required to enable quick and trouble-free deployments of large numbers of instruments will also enable more "N" to be deployed in such environments, if not Large N.

■ General considerations for Large N:

- There are not enough sensor/digitizer packages currently available to the academic community for large N, particularly for sensors with periods > 1s and for three-component sensors of any frequency range.
- For passive recording experiments with intermediate-period sensors, logistical difficulties associated with deploying and maintaining stations have generally limited such experiments to fewer than ~100 sensors.
- For active-source experiments, Large N has been in the realm of 2000-5000 sensors (such as the recent Salton Sea experiment), which has maxed out the IRIS Portable pool but only for short periods of time. Limitations of the current Texan pool include lack of 3-component sensors, limited memory, no on-board GPS timing, and limited on-board power. Increased memory, on-board GPS timing, and a better power system would enable sensor/digitizer packages to be deployed for longer periods of time, requiring fewer maintenance trips (which would decrease logistical expenses, particularly the number of people required to service sites) and significantly increase the uptime and amount of data recorded from each individual site.
- Along with Large N, there needs to be development of software and procedures for handling Large N datasets, which would at a minimum be Terabytes in size.
- In addition to small instruments, there is also a need to develop small/efficient shipping packages to enable Large N.

- Issues for BoD consideration
  - Given the importance of Large N to IRIS and its increasingly Pan-IRIS focus, there should be a working group of some sort to oversee the project. One suggestion is that this be a committee formed from members of existing Standing Committees within Instrumentation Services as well as 1-2 members from the BoD, as well as ad hoc members from the academic community.

- No general consensus emerged as to specifications for “Large N”. Principal issues for consideration include:
    - Instrument response: This is probably the point of biggest contention, and the decision ultimately will probably be driven in part by considerations of cost per channel as well as ease-of-installation. On the low-frequency end, most attendees seemed comfortable with Large N consisting of 30-60s sensors, some argued that 1-10s sensors are what would be needed. A potential compromise would be to enable mixed-mode “Large N” deployments with smaller numbers of long-period stations (> 100s) filled in with larger numbers of intermediate-period instruments (< 30-60s). On the high-frequency end, a few attendees expressed interest in flat responses extending beyond 100 Hz.
    - There was consensus that “Large N” requires light-weight, low-power instrumentation with extended recording capabilities and on-board GPS timing.
        - Light-weight yet robust and easy-to-use instrumentation will make station installations faster and easier, both of which are required in order for Large N deployments to be logistically feasible AND to facilitate RAMP-style deployments.
        - More on-board memory allows for fewer PI servicing visits, which reduces costs and allows for instruments to be put in increasingly remote places (e.g., some/many sites in Alaska have logistical & weather-related difficulties that might limit site visits to once per year).
        - Low power consumption makes stations lighter-weight and longer-lasting, both of which would contribute to easier-to-deploy and longer-lasting experiments.
        - On-board GPS timing similarly would extend the time-span over which a station could be in operation without service runs.

- Concepts for further exploration:
    - It would be worthwhile to explore potential overlapping interests with DOE, including the potential for shared funding.
    - Similarly, it would be worthwhile to explore overlapping interests with oil/gas/other industry including the potential for shared funding.
    - It would also be good to consider interests & partnerships with the international community.