TECHNOLOGY DEVELOPMENT FOR COMPUTATIONAL RADIO ASTRONOMY: 2010-2020

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Abstract

This document describes two specific areas of enabling technology development in the area of computationally-intensive observational radio astronomy that are critical to meeting the science goals of large survey telescopes currently planned or proposed for the coming decade. Theses two areas of technology development are: i) scalable radio astronomical processing in the petascale regime; and ii) techniques for ulta-high fidelity interferometric calibration and imaging. These areas of technology focus are highlighted for their importance to the associated science objectives of both current and future radio telescopes including SKA pathfinders such as the ATA and EVLA, because of the opportunities they offer for timely synergistic collaboration with other academic disciplines and industry, but also because they are areas in which there is a significant gap between current practice and anticipated scientific need in the decade 2010-2020.

Timeliness, critical observations and scientific opportunities

The fundamental open questions in contemporary astrophysics over the coming decade, such as the nature of dark energy and the formation and evolution of the universe, are driving observational astronomy across many wavelength bands to surveys over large cosmic volumes in angular and redshift coordinates (Ω, z) with fine synoptic time-sampling Δt, and high levels of completeness.

Observational radio astronomy in the coming decade will be a key participant in the exploration of these basic science questions, complementing studies in other wave-bands, but contributing specifically in areas in which radio observations have unique scientific advantages. At meter to centimeter wavelengths, radio astronomy can map neutral hydrogen from the epoch of reionization to the present time in deep surveys that are intrinsically spectroscopic and have low levels of systematic imaging error. In addition, early galaxies are uniquely accessible at millimeter wavelengths. These scientific areas are ripe for development in the coming decade given the currency of these open scientific questions and their key role in foundational astrophysics.

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Common issues in processing and computation across all wave-bands for the observational projects of the coming decade include:

- i) large-scale data management,
- ii) distributed, massive storage and federated databases,
- iii) high-speed network connections,
- iv) long-term data curation support,
- v) community software development,
- vi) data mining, reduction and analysis tools,
- vii) common data access protocols (e.g. Virtual Observatory); and
- viii) open and equitable community scientific access.

These requirements flow naturally from the implied data rates, processing, and access requirements posed by this new class of observations. These needs have common origins across all wavelengths, namely exponential increases in receptor count (where a receptor could be a CCD pixel or a radio astronomy feed element), a migration of the software-hardware boundary closer to the receptors in contemporary telescope designs, high-throughput survey operations modes, and large resultant catalogs of order 10^9 or more objects.

These broader issues for data-intensive telescopes of the next decade also apply strongly to the large radio-interferometric survey telescopes discussed here and we urge the Decadal Survey to include these telescopes in their wider consideration of these general issues. In this white paper however, we advocate for ***specific technologies in computational radio astronomy that are key to the science goals in 2010-2020 described above,*** and argue for new funding strategies to address their development.

Key technologies for computational radio astronomy: 2010-2020

The timely and critical scientific opportunities in the coming decade will require key investments in specific technologies for computationally-intensive radio astronomy if they are to be realized. This is particularly true for technologies where the state of practice differs greatly from future need, where the science yield is particularly marked, and where there are compelling opportunities for synergies with other academic disciplines and industrial partners during the decade. We present two such areas of technology development here:

1) Scalable radio astronomical processing in the petascale regime

Moore's Law has relentlessly propelled the frontier in computing performance along an exponential trajectory (Moore 1965). High-end computing (HEC) systems with tens of petaflop (10^{15} floating-point operations per second) peak performance will be available in mid-decade, with profound implications for astronomy. The availability of computing performance at this level has revolutionized the practice of science as a whole (Atkins et al. 2003), but it poses acute challenges for individual disciplines, including computational radio astronomy. Exaflop-level processing will be required, for example, for the SKA late in the decade.

Effective utilization of HEC computing at extreme scales, as will be required for large radio survey interferometers planned for the next decade, requires imaging and non-imaging analysis algorithms with high scalability. A scalable algorithm is one that can utilize available peak HEC resources without appreciable loss of efficiency. This requires significant targeted investment in scalable, parallelized algorithms and their efficient mapping to underlying HEC architectures, which are not static over time. Experience across the physical sciences in high-performance computing (HPC) indicates clearly that this investment is needed if the transformational science enabled by extreme levels of computing performance is to be achieved in practice. We will face this problem in observational astronomy within the next decade.

For a generic next-generation interferometric survey telescope, with N_{ant} antennas of diameter, D, over a maximum baseline length, B, and with N_{ch} spectral channels, the first-order scaling relation for peak imaging computing costs with uniform sensitivity over the full field-of-view, increases proportionally to: $N_{ant}^2 N_{ch} B^2$ (see Perley & Clark 2003, Cornwell 2004, Cornwell 2008). Computing costs in the tens of petaflops are readily obtained for even the first 10% of a proposed array such as the SKA; as noted above, this particular telescope will reach exascale computing needs in full implementation.

This is a particular and specific risk for radio astronomy as the instruments of the coming decade will require a large increment over current practice. At present, peak computational requirements for reducing a single dataset are frequently in the teraflop regime and the scalability requirement, if parallelized, typically does not exceed of order 10^{2-3}. This is mostly an historical artifact: the most prominent radio interferometer, the Very Large Array (VLA), although requiring leading-edge computing in the early 1980s, did not evolve significantly in output data rate (and associated computational requirements) post-construction. This is changing significantly at present, however, as the VLA correlator is being replaced as part of the EVLA project.

For radio astronomy to form part of the scientific revolution that will be enabled by extreme-scale HEC systems in the next decade requires preparedness and investment within the discipline, as well as the establishment of strong inter-disciplinary research programs and industrial collaborations.

To understand the problem of scalability it is important to consider anticipated HEC architectures over the time-scale considered by the Astro2010 Decadal Survey. HEC systems in the next decade will achieve extreme-scale performance through an unprecedented degree of concurrency. The rate of increase in peak scalar performance of individual processors has slowed significantly since 2004 as a result of on-chip power dissipation limits. By mid-decade in 2015, it is possible that petascale systems will have of order 10^6 processor cores, increasing by perhaps a factor of ten toward the end of the decade. The total number of executing threads will be likely an order of magnitude higher than the number of physical processor cores. In addition to high levels of concurrency, it is also very likely that HEC systems of the coming decade will have a relatively high degree of processor heterogeneity due to the use of integrated hardware accelerators or custom processors, such as FPGAs or GPUs. It is also likely that HEC systems will have deep memory and I/O hierarchies that will have highly asymmetric resource access times.

Collectively, these architectural considerations require imaging and non-imaging analysis algorithms in computational radio astronomy that:

i) can scale over 10^{5-7} processor cores without significant loss of performance;
ii) can exploit integrated heterogeneous processing elements to reduce cost;
iii) are robust against hardware failure (as is increasingly necessary in the case of extreme concurrency); and,
iv) are cognizant of, or optimized for dynamic or static load-balancing (the efficient allocation of work amongst threads).

Jointly, these considerations argue strongly that computational radio astronomy needs investments in this area if we are to achieve our own disciplinary science goals outlined above, but also to participate fully in the broad-based scientific revolution promised by extreme-scale computing over the coming decade.

2) **Ultra-high fidelity interferometric calibration and imaging:**

A second technology development area in computational radio astronomy in which there is a gap between the current state of practice and that required by the science goals outlined above is that of ultra-high dynamic range wide-field imaging. The future survey interferometers will require an imaging dynamic range of 10^{5-7}:1 in routine, automated, survey processing. This dynamic range is driven by the expected source populations in both large scale HI and continuum surveys.

Only a limited number of radio-interferometric images with dynamic ranges of 10^{5-6}:1 have been produced with current instruments, and then typically only at the center of the field of view (or image), and after significant interactive analysis by highly-experienced radio interferometry experts. This mode of reduction is not tenable for telescopes under consideration for the next decade, both as a result of the data rates but, more importantly, on the grounds of inequitable access this data analysis requirement poses on the full community at large. A significant step in routine dynamic-range performance is required on an accelerated time-scale.

The areas in which algorithmic investment are required are known to lie in several key areas, including, but not limited to:

i) the routine use of direction-dependent instrumental gain corrections in radio-inteferometric calibration and imaging; this is an active area of current research (Bhatnagar et al. 2008), and represents a fundamental change from the simpler visibility-plane calibration customarily undertaken with current arrays;
ii) advances in multi-resolution, multi-frequency deconvolution and imaging;
iii) real-time calibration and processing, as data rates will preclude archiving substantial quantities of raw visibility data;

iv) accurate instrumental parametrization models and their robust solution;
v) identification and removal of RFI, especially low-level RFI that is difficult to separate from signal;
vi) accurate propagation models, especially for the ionosphere; and,
vii) estimation of fidelity in interferometric imaging.

We note that calibration and imaging for the instruments discussed in this document will implicitly need to be wide-field, wide-band, and in full Stokes polarization, and the algorithmic areas of research noted above include this assumption.

In the general area of radio astronomy algorithm development for the next decade, we specifically draw attention to the need for matching efforts in non-imaging analysis, especially given the science goals above in the largely-unexplored area of transient detection and analysis. This field of discovery will be dramatically expanded by telescopes of the coming decade, as part of the broader science goals described earlier.

Based on historical precedent and experience with existing radio interferometers, algorithmic advances proceed relatively slowly, perhaps at the level of an order of magnitude improvement in imaging dynamic range per 10-15 year interval. These algorithmic advances are key however to achieved science in radio interferometry, and include such fundamental tools as self-calibration and deconvolution in current wide use in the field. Given the anticipated increment in imaging dynamic range and sensitivity required by current and future telescopes in the coming decade, a sustained investment of resources in this area throughout the decade is essential if the proposed science goals are to be met on that time-scale.

Level of effort and programmatic implications

Both areas of technology focus discussed here are fundamentally inter-disciplinary in nature; sustained investment in these areas requires care in broadening disciplinary funding opportunities in astronomy to encourage continuous research and development activity in these areas, especially in collaboration with related efforts in computational science and engineering disciplines and industrial partners. Absent sustained funding opportunities, these algorithmic efforts tend to peak during telescope design, development, and commissioning phases, but to proceed more slowly outside of these periods. This tends to "freeze-in" an age profile in the practitioner community, strongly correlated with major telescope construction cycles, but both technology areas described here are clearly fields of research from which astronomy would benefit from a more continuous injection of younger researchers. The university community is a particularly good environment in which to stimulate such collaborative, inter-disciplinary research.

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