High Resolution Near Real Time Image Processing and Support for MSSS Modernization

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ABSTRACT

This paper describes image enhancement software applications engineering development work that has been performed in support of Maui Space Surveillance System (MSSS) Modernization. It also includes R&D and transition activity that has been performed over the past few years with the objective of providing increased space situational awareness (SSA) capabilities. This includes Air Force Research Laboratory (AFRL) use of an FY10 Dedicated High Performance Investment (DHPI) cluster award -- and our selection and planned use for an FY12 DHPI award. We provide an introduction to image processing of electro optical (EO) telescope sensors data; and a high resolution image enhancement and near real time processing and summary status overview. We then describe recent image enhancement applications development and support for MSSS Modernization, results to date, and end with a discussion of desired future development work and conclusions. Significant improvements to image processing enhancement have been realized over the past several years, including a key application that has realized more than a 10,000-times speedup compared to the original R&D code -- and a greater than 72-times speedup over the past few years. The latest version of this code maintains software efficiency for post-mission processing while providing optimization for image processing of data from a new EO sensor at MSSS. Additional work has also been performed to develop low latency, near real time processing of data that is collected by the ground-based sensor during overhead passes of space objects.

1. INTRODUCTION

This document addresses and represents the work of a dedicated team that has been working over the past several years to transform image enhancement software from basic research to usable and additionally-enhanced high performance computing (HPC) software applications. The applications software and utilities addressed by this publication are utilized to process atmospherically-blurred raw images of space objects obtained from ground-based electro-optical telescope sensors, such as MSSS, and perform additional image processing to obtain high resolution imagery information. The Air Force Maui Optical & Supercomputing (AMOS) including MSSS is helping to increase the nation's SSA capabilities using advanced electro optical-based collection and analysis technologies and is a national focal point for ground-based space SSA. This is a project of the AFRL Directed Energy Directorate, with the work being accomplished by a distributed team led by AFRL/RD; and performed by the AFRL/RD Directed Energy Directorate, AFRL/RI Information Directorate, and AFRL contractor personnel.

2. HIGH RESOLUTION IMAGE ENHANCEMENT and NEAR REAL TIME PROCESSING

AMOS is continuing to provide enhanced image quality, utilizing the PCID image processing and user interface software packages that were developed by AFRL [1]. PCID stands for Physically Constrained Iterative Deconvolution and is an implementation of a multiple frame blind deconvolution technique.

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14. ABSTRACT

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The PCID algorithm uses little or no a priori information about the objects that are being imaged and incorporates features that increase the probability and speed of finding the global minimum, achieve super resolution by de-aliasing, process non-idealities such as spatially-cropped images due to jitter and/or object size relative to the detector size, and generate many of the PCID inputs automatically [2]. The forward model used in the PCID algorithm is the standard linear imaging model. Multiple frames of data are collected by sensors using telescopes such as at MSSS, while the object, in this case the shuttle, passes overhead. Each collected frame is blurred by the earth's atmosphere. The name given to this blurring is point spread function (PSF). Frames are grouped together to form an ensemble where the object is constant throughout all frames. PCID jointly estimates the common object and the blurring from each frame by iteratively estimating the object and the blurring per frame. The object and PSF estimates more closely match the collected frames with each processing iteration cycle. Physical constraints, such as object positivity, use of support for the object and PSF as well as noise weighting contribute to fast convergence to the object estimate. PCID is best accessed by image analysts and other users through a Net-centric or Web user interface and job management system that has been co-developed with PCID called ASPIRE (Advanced Speckle Image Restoration Environment). The output of interest is an enhanced image, or recovery, of the object. PCID developers also researched and created Cramér–Rao estimation theory and statistics lower bound (CRB) expressions for blind deconvolution and carried out a comparison study that showed that PCID closely approaches these theoretical limits when run in the non-blind mode and should be able to approach the theoretical limits in the blind mode when regularization and positivity is employed. A high level graphic of PCID and ASPIRE is shown in Fig. 1.

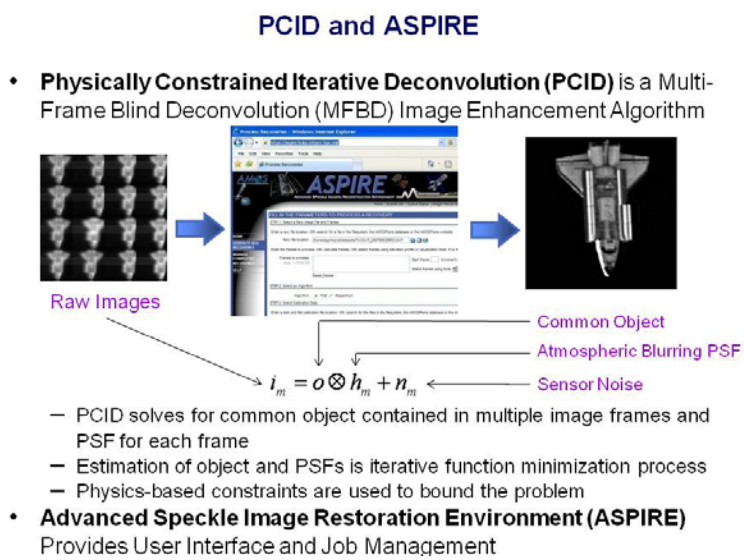


Fig. 1. PCID and ASPIRE

Isoplanatic MFBD is another version of the MFBD algorithm. This algorithm performs a joint estimation of object and PSF (or its Fourier transform, the transfer function) parameters, and can use either Zernike or Spatial model PSFs. Like PCID, this algorithm also uses the Conjugate Gradient minimizer and is also based on Limited Memory Broyden Fletcher Goldfarb Shannon Bounded (LBFGSB) Limited Memory Quasi-Newton routines.

PCID and ASPIRE are continuing to utilize a DOD High Performance Computing Modernization Program (HPCMP) FY10 Dedicated High Performance Investment (DHPI) platform with characteristics as outlined below.

- DOD HPCMP FY10 DHPI Award − *Kaku*
- Repurposed and Upgraded Former MHPCC DSRC *Jaws* Nodes
  - 150 Power Edge 1955 Compute Nodes; Intel Xeon Woodcrest Dual-Core Processors
  - 8 GB/Core Upgraded Memory
  - 600 Cores
  - Single Data Rate Infiniband, Gig-E Interconnect
  - Linux Red Hat OS
  - 36 TB Direct-Attached Storage

The *Kaku* platform is shown in Fig. 2 which follows.

Fig. 2. FY10 Dedicated High Performance Investment (DHPI) *Kaku* System

PCID v9 and ASPIRE were installed on *Kaku*, and transitioned for use by image analysts during 2010. This milestone was documented in the Air Force Research Laboratory *AFRL Technology Milestones* "New Focus on Space Object Identification" dated 15 June 2010. http://www.wpafb.af.mil/news/story.asp?id=123209405

Our image enhancement team has continued to maintain and utilize PCID and ASPIRE to continue to perform R&D for improved performance. The PCID performance improvements over the recent years are summarized in the results to date discussion and significance section of this paper. These packages are also used as described directly above to obtain high quality images and to provide quick turnaround high throughput post-mission processing of an entire space object overhead pass in less than 30 minutes. The increased resolution and qualify of imagery, which has been processed with the enhanced PCID algorithm and the FY10 DHPI HPC platform at MHPCC DSRC is shown in Fig. 3.

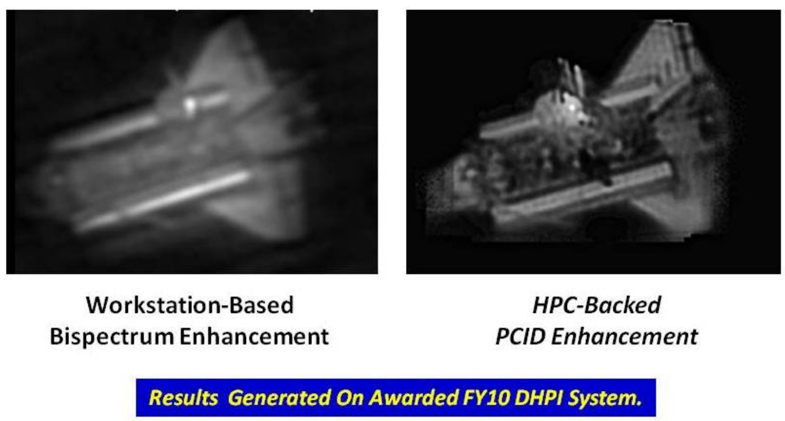


Fig 3. HPC-Backed PCID Provides Increased Image Quality

Our team has also made significant developmental progress on the next generation of image enhancement service called the Inline Speckle Imaging Reconstruction Engine (INSPIRE). While we've leveraged a great deal of what we did for PCID/ASPIRE, the INSPIRE software suite supports a fundamentally different concept of operations (CONOPS). ASPIRE was designed for batch post-processing, where the emphasis was on total throughput. It did not matter how long an individual reconstruction took as long as the entire pass was processed within 30 minutes. This throughput requirement drove the processing technique to a coarse-grain parallelization approach where individual image reconstructions were performed almost serially. This current CONOPS is depicted in Fig. 4.

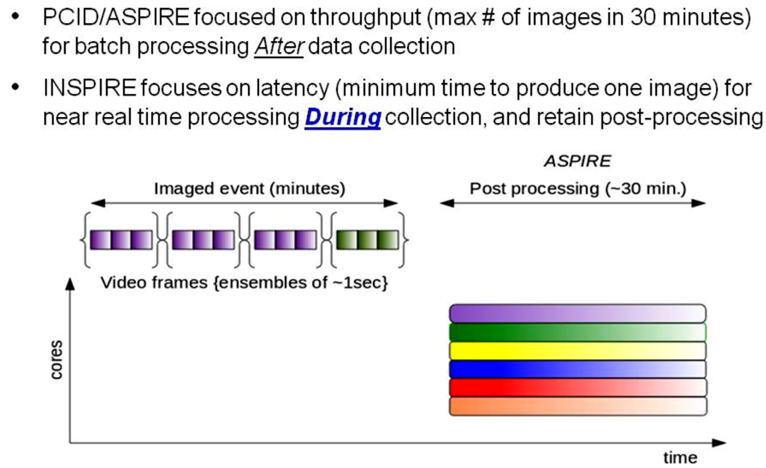


Fig. 4. PCID/ASPIRE High Resolution Post-Processing

PCID and related software utilities have been upgraded with algorithm improvements, code streamlining, using faster minimizers and optimized math libraries, improved parallelization and improved calibration codes. The software has been accelerated to the point where we can change the concept of operations to low-latency, near real time (NRT) processing. INSPIRE is being developed to provide low latency, high resolution, NRT processing so we can process images -- as they flow from the sensor. To achieve this, we are pushing on multiple levels of parallelism. We have determined that NRT processing is best suited to multiple instances of parallel PCID which spreads frames in the ensemble across nodes to reduce latency to provide the highest processing/resolution and exploitable imagery. The INSPIRE goal is to achieve NRT processing during telescope data collection -- with processing pipeline latencies of less than 12 seconds. We use parallelization within the image reconstruction code to drive down the total processing time on a per-image basis. We then use multiple reconstructors, processing in parallel in "cliques" to keep up with the cadence of the input data rate. The end result is that the operator on the loop can change parameter settings on the fly and almost process the imagery like one does with movies. The Fawkes/Phoenix near real-time information management services software that the AFRL Information Directorate has implemented and brought to our collaborative team [3] has also been a key enabler for our significant INSPIRE achievements. As such, INSPIRE combines PCID, PARSEC, and MFBD algorithms and Web service concepts; and also utilizes the Fawkes/Phoenix middleware and Publish, Subscribe, Query (PSQ) schema.

Under INSPIRE processing, if we are able to realize a process latency of less than one second, then all compute cores operate on and as a single "clique" of image frames data as illustrated in Fig. 5, which follows.

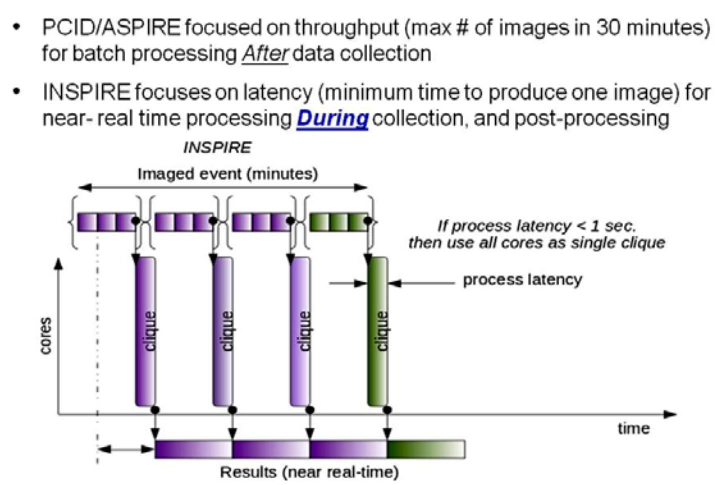


Fig. 5. INSPIRE Processing for Less Than One Second Latency

If process latency is greater than one second, then INSPIRE will assign multiple, staggered cliques for compute processing as shown in Fig. 6. The ability to perform additional post-processing is still retained.

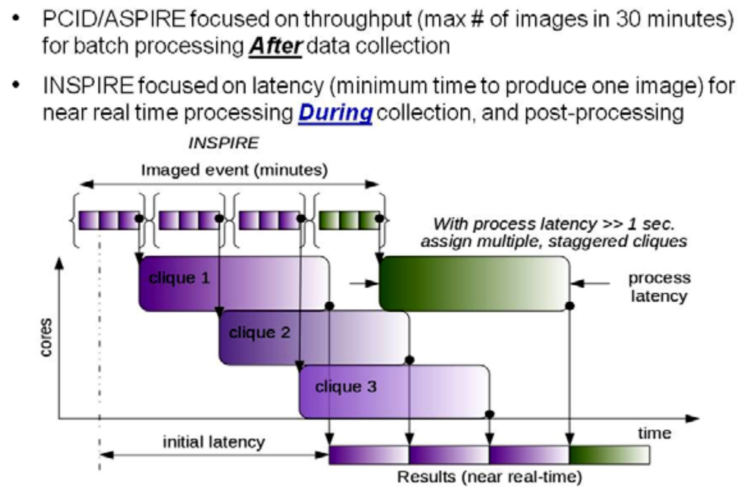


Fig. 6. INSPIRE Processing for Greater Than One Second Latency

The developmental version of INSPIRE has been demonstrated with the Fawkes communications system several times since calendar year 2011 to various stakeholders that involved the image enhancement algorithm processing time, and the total end-to-end latency. Two particular experiments were performed, and subsequently addressed in papers and presentations [3, 4,] that demonstrated system behavior; with details of the processing, communications, and metrics captured. To summarize, for these experiments 20 ensembles of imaging data were input into the system. One node was used for executing the clique coordinator software (CC) and four clique master (CMs). Two additional nodes with 8 cores each were used to implement four processor cliques, with each clique having 4 cores. Each of the 4 cliques was assigned to a respective CM. The experiments were performed at the Maui High Performance Computing Center on the *Mana* dual-quad Xeon Nehalem HPC system with 24 GB of RAM on each node. PCID has been optimized to run in parallel, with runtimes reduced from hours to seconds. Overall timing results for the 20 Ensemble/ 2 (Every two seconds one of four CMs launched a PCID run on its respective backnodes) second experiment showed overall end-to-end processing timing of 4.93 to 8.57 seconds. INSPIRE demonstrations and experiments have also included use of a Web-based thin client INSPIRE Viewing Utility (IVU) capability that was developed. The INSPIRE capability has also been executed and demonstrated on the AFRL/RI heterogeneous supercomputer, *Condor*. This platform includes 78 Intel Xeon X5650 dual-socket hexa-core processors; 1,716 Sony Playstation III® (PS3) game console processors; and 168 General Purpose Graphical Processing Units. [5].

The MSSS Modernization and upgrades previously discussed in this paper, which have occurred in calendar year 2011 and 2012, included new/upgraded infrastructure and sensors, including the 1.6 meter telescope new "*FLASH*" sensor and camera, which provides imaging and Wide Field of View (FOV) for multiple development and mission applications. This camera provides several new benefits that include using Electron-Multiplying Charge Coupled Devices (EMCCD) for increased gain and lower readout noise. It operates at 35 frames per second for full resolution, but can perform up to 549 frames per second. Modifications to PCID, ASPIRE, and another image enhancement algorithm, Parallel Bispectrum (PARSEC) were needed, as many new data headers in the camera sensor information files were not the same as previous MSSS sensors. The new MSSS *FLASH* sensor uses more of the instrument array as the FOV is increased so that sampling at larger fields of view is correct. This results in *FLASH* frames that vary from 128 x 128 pixels up to 512 x 512 pixels. Each pixel is 16 x 16μm with a maximum readout rate of 10 MHz. Many tasks were identified regarding the ASPIRE, PCID, and PARSEC software engineering that needed to be performed on the image enhancement calibration, ensemble generation, algorithms, and other utilities modifications needed. These items are addressed further below in the next section of this paper.

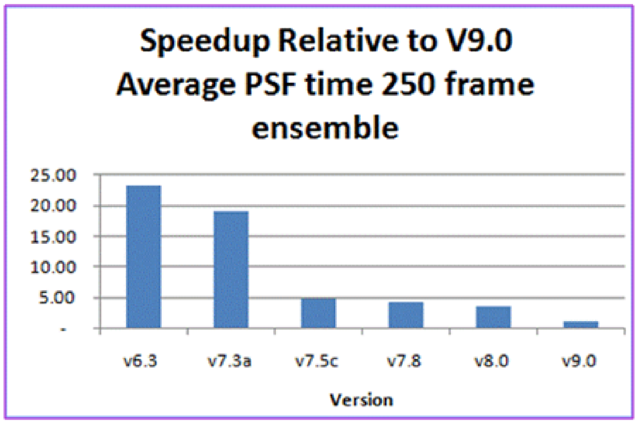
3. IMAGE ENHANCEMENT APPLICATIONS AND SUPPORT FOR MSSS MODERNIZATION

As introduced in the previous section above, a review of calibration, ensemble generation (ensembles of camera picture frames), and modification of algorithms and other software utilities work was needed and performed as outlined below.

- Review *FLASH* sensor and calibration process to Flexible Image Transmission (FITS) files
  - Review subtracted background level values written to header for data debias
  - Modify PCID, PARSEC as needed, obtain proper read noise values for each sensor, calculate ideal threshold values for display, and develop PSF initial setting for PCID for all FOV
  - Develop code within ASPIRE to reduce the calibration data and calibrate FLASH data files, and to convert HDF formatted files to FITS.
  - Modify the ensemble generator and ASPIRE as needed to function properly with *FLASH* and SOR data
    - PCID and Parallel Bispectrum (PARSEC) codes require adding the photon count of the bias removed from each frame to the header for that frame for the new *FLASH* sensor. The read noise for the sensors is also needed.
  - Correctly read exposure time from header so ensembles can be formed using seconds
  - Remove the derotate step when unnecessary
  - Allow embed and no star option for PARSEC - when separate ensembles are formed (derotate on) copy all data headers to separate ensembles
  - Adjust run times for recoveries and batch job submittals
  - Ensure that calibrated FITS files are allowable entries for object and star data and that the correct sensor type is read from FITS headers
  - Ensure that the Q data parameter (scaling parameter based upon sampling rate of the data and value used to scale all Fourier domain quantities) is correctly set in the namelist.
- Review PARSEC and PCID submit pages for efficient and valid processing for these sensors
- Create new release versions PCID v11.0 and PARSEC v8.0 (the new PARSEC version of will add an embed function to handle clipped frames and/or large object data) for *FLASH* sensor data, regression test and install on *Kaku* - ensuring GEMINI and AEOS data reduction is still valid.
- Ensure the data recovery movie viewer works correctly with various sensor sizes with and without embed, ensure recoveries display correctly in ASPIRE, where analysts do not have any way to change the range of the display, and keep recovery integrity by not suppressing fine detail of the recoveries
- Ensure FITS-to-Tagged Image File Format (TIFF) conversion utility works correctly to write all required parameters to TIFF output files and that all header tags pass through calibration to TIFF-PL data.

4. RESULTS TO DATE DISCUSSION AND SIGNIFICANCE

Significant improvements to image processing enhancement have been realized over the past several years. The PCID software has realized more than a 10,000-times speedup compared to the original R&D code, and a speedup of greater than 72-times has been achieved between calendar years 2008-2011 [6]. Example performance speedup metrics information is shown in Fig. 7, which follows. The speedups relative to v9.0 are for using average Spatial PSF estimation.



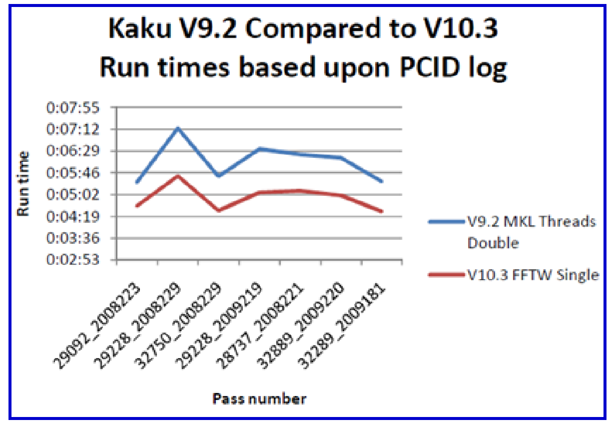


Fig. 7. PCID v9 and PCID V10 Optimizations Results

PCID v11.0 and PARSEC v8.0 development was completed by April 2012. PCID v11.0 is comprised of 11,970 source lines of Fortran, C, and other files. PARSEC v8.0 is comprised of 3,463 source lines of Fortran, C, and other files. The PCID v11.0 image processing regression testing performance using standard data sets provides equal or better image recoveries than the previous PCID version. PCID v10 provided a 20% speedup in code execution and PCID v11.0 provides more than a 10% additional speedup over the PCID v10 version. The team ported all software to *Kaku* and completed regression testing on this DHPI platform environment. The PCID automatic calculations for object support, filter cutoff, point spread function support, and other items were verified and adjustments made as necessary to these parameters to deliver the best overall recoveries using the automatic parameters.

MSSS modernization support tasks were performed so that this latest version of PCID further improves the efficiency of the code as noted above while providing optimization for the new *FLASH* sensor at MSSS. ASPIRE was also updated for PARSEC to include a “no star” option, if reference star calibration is not needed or viable. This PARSEC update added correction for the object amplitudes based on values derived from the data which eliminates star measurement. ASPIRE, PCID, and PARSEC ensemble generator and parameters selection software modifications and new developments to process calibration data, calibrate FLASH data files, and convert HDF formatted files to FITS were successful. Work also involved analyzing and understanding HDF5 files format and array dimension sizes and order, and the HDF5 data constructor. Code modifications were also performed to the validate file Common Gateway Interface (CGI) script code component to account for the various new data types so that the software can flexibly read the header of FITS files to set the sensor in the validate CGI software.

Our latest image enhancement software provides significant capabilities for yet further improved delivery of high resolution products. We would also like to continue development, improvement, and demonstration of the Inline Speckle Imaging Reconstruction Engine (INSPIRE), which will have the capability to run two image processing algorithms simultaneously, as priorities and funding allows. A developmental user interface screenshot from previous INSPIRE demonstrations that were addressed previously in this paper is shown in Fig. 8, which follows.

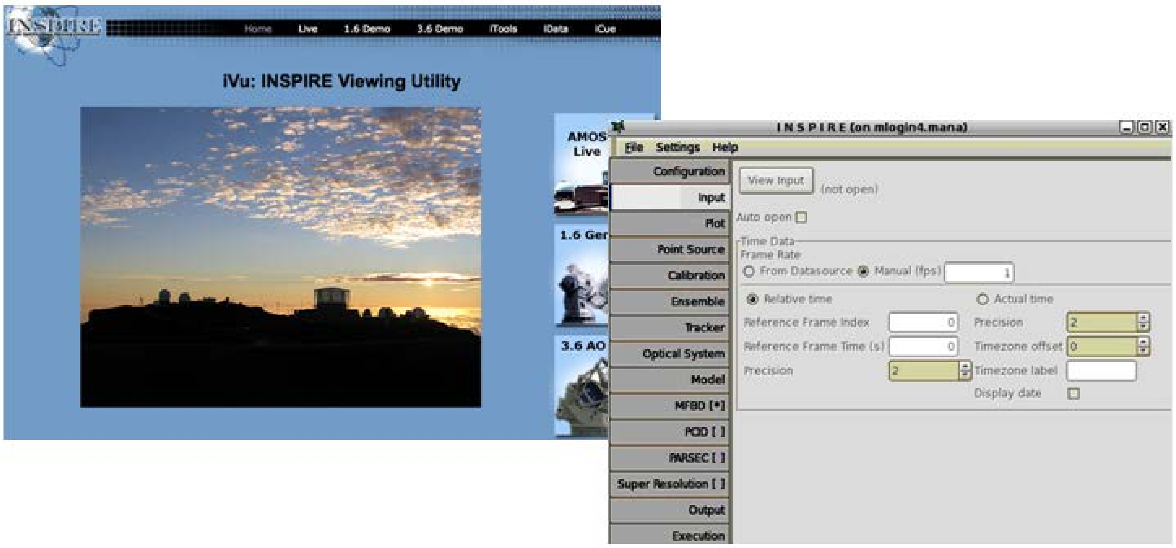


Figure 8. INSPIRE Viewing Utility and INSPIRE

Additional INSPIRE work includes developing a robust, user-ready application for missions and hardening the existing algorithms, improving the integration and documentation, and providing more customer-focused demonstrations.

Further development could include incorporating a richer feature set for an updated and New INSPIRE Viewing Utility (NiVU) Web-based thin client for remote viewing, management, and integration with databases for archiving appropriate input and output data. NiVU utilizes Google Web Toolkit (GWT) open source development software development kit for building and optimizing complex browser-based applications. GWT provides a set of core Java APIs and Widgets that allow developers to write Asynchronous JavaScript and XML (AJAX) Web applications in Java and then compile the source to highly optimized JavaScript that runs across all browsers. The foregoing INSPIRE software items may then be available for porting the updated software to the AMOS *Kaku* system, then to the upcoming '*Lilikoi'* platform. Other user interfaces, cross-platform application framework technologies, and management tools may also be evaluated and implemented.

5. CONCLUSIONS

Our team has successfully updated image enhancement software for MSSS modernization that is available for use. We continue to provide improved SSA technologies and capabilities that leverage HPC. We anticipate the arrival of the new FY12 DHPI HPC platform, *Lilikoi,* during the third quarter of calendar year 2012, when our team plans to prepare for and port image enhancement software and other utilities to the new platform for continued R&D and availability for mission support. We would also like to continue to progress further towards providing even more capable SSA HPC Service Oriented Architecture (SOA) services and end-to-end NRT processing and demonstrations, as may be directed by the government.

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