The Suomi National Polar-orbiting Partnership (SNPP): Continuing NASA Research and Applications

James Butler
NASA Goddard Space Flight Center, Greenbelt, MD

James Gleason
NASA Goddard Space Flight Center, Greenbelt, MD

Gary Jedlovec
NASA Marshall Space Flight Center, Huntsville, AL

Patrick Coronado
NASA Goddard Space Flight Center, Greenbelt, MD

Executive Summary

The Suomi National Polar-orbiting Partnership (SNPP) satellite was successfully launched into a polar orbit on October 28, 2011 carrying 5 remote sensing instruments designed to provide data to improve weather forecasts and to increase understanding of long-term climate change. SNPP provides operational continuity of satellite-based observations for NOAA's Polar-orbiting Operational Environmental Satellites (POES) and continues the long-term record of climate quality observations established by NASA's Earth Observing System (EOS) satellites. In the 2003 to 2011 pre-launch timeframe, NASA's SNPP Science Team assessed the adequacy of the operational Raw Data Records (RDRs), Sensor Data Records (SDRs), and Environmental Data Records (EDRs) from the SNPP instruments for use in NASA Earth Science research, examined the operational algorithms used to produce those data records, and proposed a path forward for the production of climate quality products from SNPP. In order to perform these tasks, a distributed data system, the NASA Science Data Segment (SDS), ingested RDRs, SDRs, and EDRs from the NOAA Archive and Distribution and Interface Data Processing Segments, ADS and IDPS, respectively. The SDS also obtained operational algorithms for evaluation purposes from the NOAA Government Resource for Algorithm Verification, Independent Testing and Evaluation (GRAVITE). Within the NASA SDS, five Product Evaluation and Test Elements (PEATEs) received, ingested, and stored data and performed NASA's data processing, evaluation, and analysis activities. The distributed nature of this data distribution system was established by physically housing each PEATE within one of five Climate Analysis Research Systems (CARS) located at either at a NASA or a university institution. The CARS were organized around 5 key EDRs directly in support of the following NASA Earth Science focus areas: atmospheric sounding, ocean, land, ozone, and atmospheric composition products. The PEATES provided the system level interface with members of the NASA SNPP Science Team and other science investigators within each CARS. A sixth Earth Radiation Budget CARS was established at NASA Langley Research Center (NASA LaRC) to support instrument performance, data evaluation, and analysis for the SNPP Clouds and the Earth's Radiant Budget Energy System (CERES) instrument.

Following the 2011 launch of SNPP, spacecraft commissioning, and instrument activation, the NASA SNPP Science Team evaluated the operational RDRs, SDRs, and EDRs produced by the NOAA ADS and

IDPS. A key part in that evaluation was the NASA Science Team's independent processing of operational RDRs and SDRs to EDRs using the latest NASA science algorithms. The NASA science evaluation was completed in the December 2012 to April 2014 timeframe with the release of a series of NASA Science Team Discipline Reports. In summary, these reports indicated that the RDRs produced by the SNPP instruments were of sufficiently high quality to be used to create data products suitable for NASA Earth System science and applications. However, the quality of the SDRs and EDRs were found to vary greatly when considering suitability for NASA science. The need for improvements in operational algorithms, adoption of different algorithmic approaches, greater monitoring of on-orbit instrument calibration, greater attention to data product validation, and data reprocessing were prominent findings in the reports. In response to these findings, NASA, in late 2013, directed the NASA SNPP Science Team to use SNPP instrument data to develop data products of sufficiently high quality to enable the continuation of EOS time series data records and to develop innovative, practical applications of SNPP data. This direction necessitated a transition of the SDS data system from its pre-launch assessment mode to one of full data processing and production. To do this, the PEATES, which served as NASA's data product testing environment during the prelaunch and early on-orbit periods, were transitioned to Science Investigator-led Processing Systems (SIPS). The distributed data architecture was maintained in this new system by locating the SIPS at the same institutions at which the CARS and PEATES were located. The SIPS acquire raw SNPP instrument Level 0 (i.e. RDR) data over the full SNPP mission from the NOAA ADS and IDPS through the NASA SDS Data Distribution and Depository Element (SD3E). The SIPS process those data into NASA Level 1, Level 2, and global, gridded Level 3 standard products using peer-reviewed algorithms provided by members of the NASA Science Team. The SIPS work with the NASA SNPP Science Team in obtaining enhanced, refined, or alternate real-time algorithms to support the capabilities of the Direct Readout Laboratory (DRL). All data products, algorithm source codes, coefficients, and auxiliary data used in product generation are archived in an assigned NASA Distributed Active Archive Center (DAAC).

NASA, as a science research organization, has developed space-borne remote sensing instruments and corresponding science algorithms to measure and quantify geophysical parameters for use in understanding and quantifying climate change. Many of these algorithms, such as those mentioned above, developed or being developed by the SNPP SIPS, are applicable for real-time regional applications. The NASA SNPP Direct Readout (DR) program for real time applications, in order to bridge the gap between NASA science and end-user applications, has developed support technologies and ported science algorithms to function in a direct readout environment for application users. Through the use of near-real-time data obtained from internet-based data centers and from the Direct Broadcast (DB) systems on the EOS and SNPP satellites, real-time environmental data are made available on a continuous basis world-wide for ready data processing given the following three elements necessary to render useful products by the general application user: instrument specific algorithms with data processing tools to handle a live data stream, data product formatting or data transport tools, and product distribution mechanisms for decision support systems enabling the use of space-borne remote sensing data for real-time applications.

The NASA DR model has identified key technology categories that the DR end-user would have to contend with in order to be compliant with a multi-satellite, multi-instrument environment. These categories include: real-time system processing tools (i.e. the International Polar-Orbiting Processing Package (IPOPP)), Consultative Committee for Space Data Systems (CCSDS) packet re-assembly and standard data reformatting tools (i.e. Real-Time Software Telemetry Processing System (RT-STPS)) and Hierarchical Data Format (HDF) to GeoTiFF (H2G)), instrument-specific calibration and geo-registration algorithms, a science processing algorithm (SPA) wrapping schema for standard system integration and sustainment, and real-time data distribution mechanisms such as Simulcast. NASA has addressed these in the form of specific technologies which are generic in nature and can be integrated into existing or developing DR systems.

In 2014, NASA held the Second Suomi NPP Applications Workshop to brief application users on upcoming data products and to exchange information between application developers, the NASA Science Team, and the new Science Investigator-led Processing Systems (SIPS) community. The workshop provided updated information on instrument performance, data characteristics, and ways to access the data, a review of current SNPP applications in use by end users and opportunities for the user community to provide feedback to NASA and the science team, and the effort to identify current barriers to the integration of SNPP data into other existing and developing applications. Much of the interaction was conducted in breakout sessions aligned with the four focus areas of Public Health and Air Quality, Water Resources, Ecological Forecasting, and Disasters. Leaders of each breakout session received input from and participated in discussions focused on a list of questions that was provided to workshop attendees.

The participants in all breakout sessions shared some common concerns that could limit the use of SNPP data for current and new applications. Many participants felt that the community still does not know to go to NASA for observations, data, and models supporting applications in the focus areas. Even if data products are provided, users may lack sufficient training and expertise for incorporating and using them in their decision-making processes. Participants recommended a "one-stop shop" for data and applications that are developed from SNPP Level 1, Level 2, or Level 3 data products. Currently, NASA Distributed Active Archive Centers (DAACs) focus on science team outputs, whereas a single portal for application outputs is not yet available. The recommendation was made that an applications portal be developed to provide data in various forms (i.e. GeoTIFF, HDF, network Common Data Form (netCDF), etc.) with limited latency and tools for search, reprojection, and subsetting. Lastly, it was recommended that SNPP products be developed with algorithms and quality assurance flags consistent with predecessor instruments (eg. the MODerate resolution Imaging Spectroradiometer (MODIS), the Atmospheric InfraRed Sounder (AIRS), etc.).

1. Introduction

The Suomi National Polar-orbiting Partnership (SNPP, formerly the National Polar-orbiting Operational Environmental Satellite System's (NPOESS) Preparatory Project (NPP)) was launched into a polar orbit on October 28, 2011 carrying 5 remote sensing instruments. These instruments include the Visible Infrared Imaging Radiometer Suite (VIIRS), the Crosstrack Infrared Sounder (CrIS), the Advanced Technology Microwave Sounder (ATMS), the Ozone Mapping and Profiler Suite (OMPS), and the Clouds and the Earth's Radiant Energy System (CERES) instrument. Currently as part of the collaborative NOAA/NASA Joint Polar Satellite System (JPSS), these SNPP instruments collect critical data to improve weather forecasts and to increase understanding of long-term climate change. SNPP provides operational continuity of satellite-based observations and products for NOAA's Polar-orbiting Operational Environmental Satellites (POES) and continues the long-term record of climate quality observations established by NASA's Earth Observing System (EOS) satellites. SNPP also provides pre-operational demonstration and validation risk reduction for instruments and data products for the follow-on Joint Polar Satellite System (JPSS) satellites.

2. Evolution of NASA SNPP Science

a. Prelaunch: 2003 to 2011

The production of well-calibrated, multi-year instrument data and science data products from the SNPP instruments has evolved directly from the work of NASA's NPP and SNPP Science teams. In the SNPP prelaunch timeframe from 2003 to 2011, these science teams assessed the adequacy of operational Raw Data Records (RDRs), Sensor Data Records (SDRs), and Environmental Data Records (EDRs) from the SNPP instruments for use in climate research, examined the operational algorithms used to produce those data records, and proposed a path forward for the production of climate quality products from SNPP. In assessing SDR and EDR climate quality, the science team used Level 1 (i.e. SDR level) and Level 2+ (i.e. EDR level) data from EOS instruments as proxy data for their SNPP counterparts (e.g. the MODerate resolution Imaging Spectroradiometer (MODIS) for VIIRS, the Ozone Monitoring Instrument (OMI) for OMPS, the Atmospheric InfraRed Sounder (AIRS) for CrIS, and the Advanced Microwave Sounding Unit (AMSU) for ATMS). These data were processed using both heritage EOS algorithms and SNPP algorithms for purposes of data product comparison and assessment.

The data flow from NOAA operations to the SNPP Science Team during this time is shown in the simplified diagram of Figure 1. In the figure, SNPP RDRs, SDRs, and EDRs were acquired in real time by NASA's Science Data Segment (SDS) from the NOAA Interface Data Processing Segment (IDPS). Long-term, archived SNPP mission data were acquired by the SDS from the NOAA Comprehensive Large Array-Data Stewardship System (CLASS), an electronic library of NOAA environmental data. Operational algorithms were obtained from the NOAA Government Resource for Algorithm Verification, Independent Testing, and Evaluation (GRAVITE). In addition to acquiring xDRs, where x is R, S, or E, from IDPS and CLASS, the SDS functioned as a distributed science data system used to assess the quality of SNPP xDRs for accomplishing climate research, to provide suggested algorithm improvements to the IDPS, and to processes selected data subsets in support of climate assessments, calibration, and validation. As such, the SDS had no operational requirements. As shown in Figure 1, the SDS had several components. Data network and transport functions were performed by the SDS Data Delivery Depository (SD3) using SDS Network Infrastructure. The Integration/Test System (I/T System) enabled SDS algorithm improvements to be reported back to the NOAA IDPS. The Product Evaluation and Test Elements (PEATEs) received, ingested, and stored data and performed data characterization and verification activities. The evaluation, analysis, and processing of SNPP data were performed by the PEATEs. As seen in Figure 1, each PEATE was physically housed within a Climate Analysis Research System (CARS). The CARS provided the SDS a fully integrated operational structure with 5 functionally independent elements and managed PEATE activities within their home institutions. The 5 CARS were organized around key EDRs (i.e. atmospheric sounding, ocean, land, ozone, and atmospheric composition products) in support of NASA Earth Science focus areas. Table 1 provides a list of EDRs mapped to each PEATE. The PEATEs provided the system level interface with members of the NPP Science Team and other science investigators within each CARS. It is through this interface that EDR algorithm improvements from science investigators were ultimately incorporated into data processing code changes within the CARS and the SDS I/T System. Also shown in Figure 1 are the NPP Instrument Support Characterization Team (NICST) housed within the SNPP Project Science Office and the Earth Radiation Budget CARS located at NASA Langley Research Center. Briefly, the NICST focused on the evaluation and analysis of VIIRS performance and calibration data, leveraging its strong heritage in performing those same functions for MODIS on the EOS Terra and Aqua spacecraft. The Earth Radiation Budget CARS located at NASA Langley Research Center (NASA LaRC) handled the processing of SNPP CERES data.

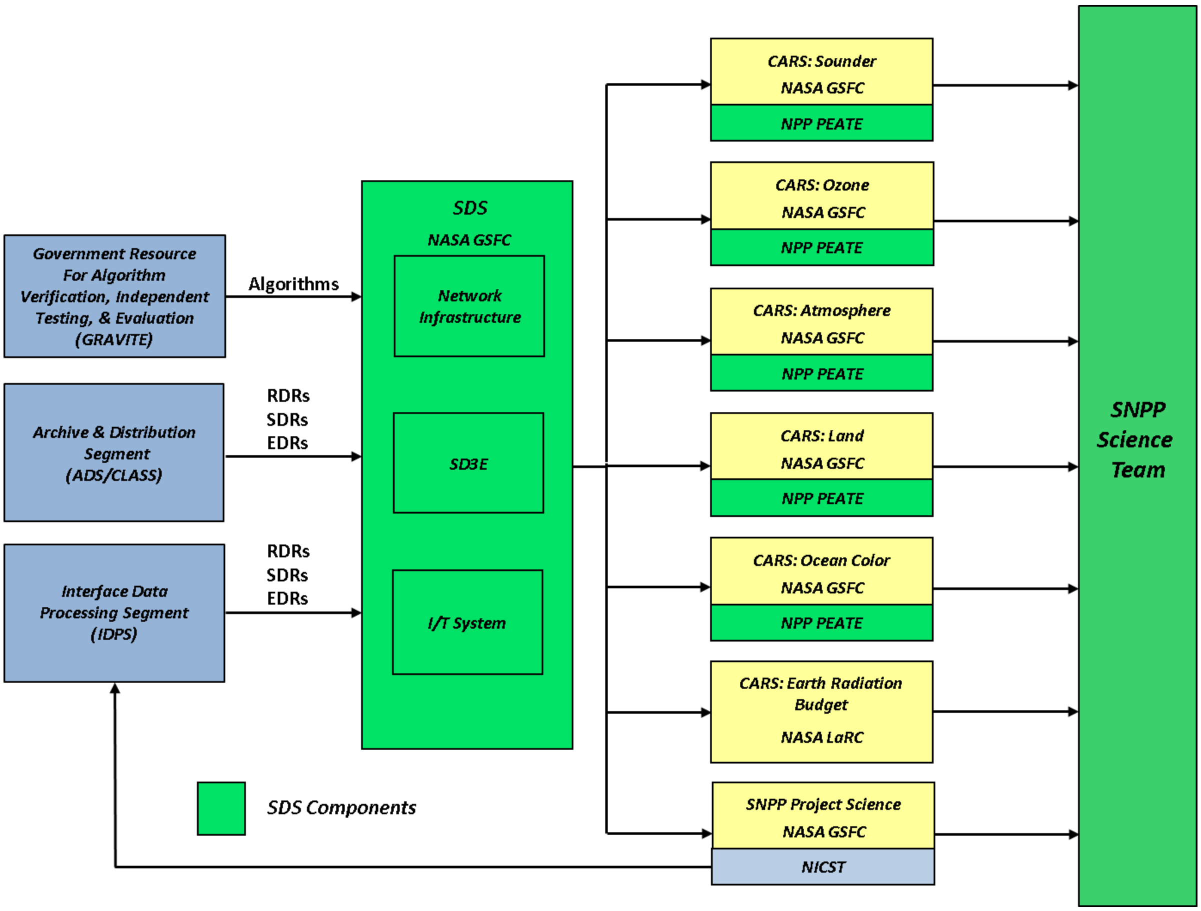

Figure 1. **SNPP data flow during NASA's assessment of the adequacy of operational Raw Data Records (RDRs), Sensor Data Records (SDRs), and Environmental Data Records (EDRs) for NASA Earth Science.**

Table 1. SNPP EDRs Mapped to PEATEs

●Ocean PEATE Ocean Color/Chlorophyll Sea Surface Temperature ●Land PEATE Albedo (Surface) Land Surface Temperature Snow Cover and Depth Surface Type Active Fires Ice Surface Temperature Vegetation Index Aerosol Optical Thickness Aerosol Particle Size ●Ozone PEATE Ozone Total Column/Profile Ozone Limb Profile	●Atmosphere PEATE Suspended Matter Cloud cover/Layers Cloud Effective Particle Size Cloud Top Pressure Cloud Top Temperature Cloud Base Height Cloud Optical Thickness ●Sounder PEATE Atmospheric Vertical Moisture Profile Atmospheric Vertical Temperature Profile Atmospheric Vertical Pressure Profile

b. Postlaunch: 2011 to present

Following the launch of SNPP, spacecraft commissioning, and on-orbit instrument activation, the NASA SNPP Science Team focussed on evaluating the actual SNPP RDRs, SDRs, and EDRs obtained from the IDPS and CLASS as to their suitability for NASA Earth system science. During this time, a subset of Science Team members also supported SNPP instrument on-orbit calibration and validation activities and examined the possible production of new data products from SNPP data. The NASA science evaluation was completed in the December 2012 to April 2013 timeframe with the release of a series of NASA Science Team Discipline Reports. These reports are available at http://npp.gsfc.nasa.gov/teaminfo.html. In summary, these reports indicated that the RDRs being produced by the SNPP instruments were of sufficiently high quality to be used to create data products suitable for NASA Earth system science and applications. However, the quality of the operational SDRs and EDRs produced from these RDRs were found to vary greatly especially when considering their suitability for meeting NASA Earth system science requirements. The science team reports identified a number of reasons for this variation in quality, including the need for improvements in existing algorithms, adoption of different, improved algorithmic approaches, and data reprocessing. The NOAA SNPP requirement for near-real time operational data processing does not support the reprocessing of SNPP instrument data required by global change science. In addition, the science team reports identified the need for increased on on-orbit instrument calibration monitoring and data product validation.

A key part in determining the suitability of RDRs and SDRs for continuing NASA Earth system science data records and applications was the NASA SNPP Science Team's independent processing of RDRs and SDRs to EDRs using the latest NASA science algorithms. The NASA Ocean Color PEATE and, more specifically, the NASA Ocean Biology Processing Group (OBPG), applied their established calibration methods, including reprocessing and algorithms based on lessons learned from the Sea-viewing Wide Field-of-View Sensor (SeaWiFS) and MODIS on the NASA Earth Observing System (EOS) Aqua satellite, in processing VIIRS data with the goal of producing the standard suite of NASA ocean color products from VIIRS that are consistent with heritage sensors. Figures 2a and b compare global ocean deep water chlorophyll *a* (i.e. Chl *a*) concentration derived from SNPP VIIRS RDRs and MODIS Aqua Level 0 data, respectively, for the month of February 2012. Figure 2c shows a comparison of the 8 day composite, deep water, mean Chl *a* trends from SNPP VIIRS, MODIS Aqua, and the SeaWiFS climatology.

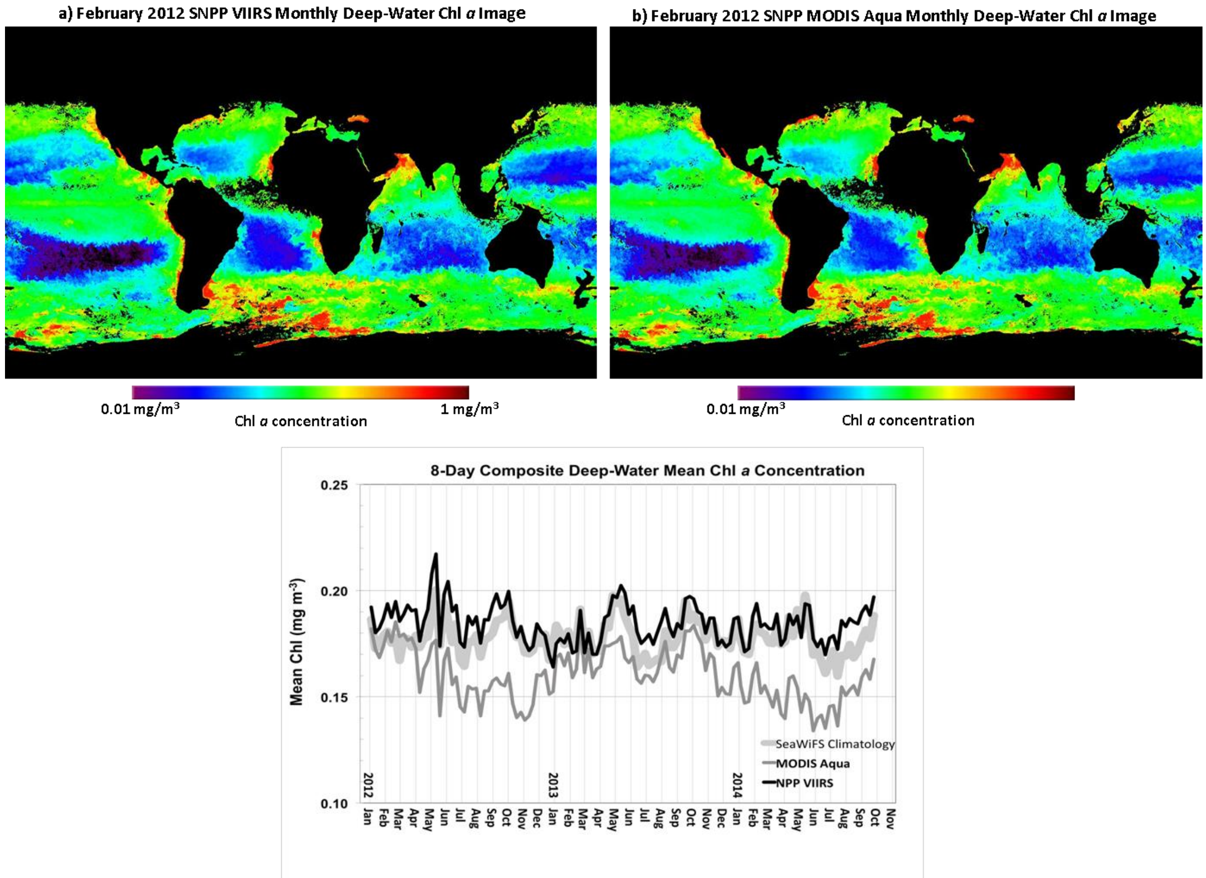

Figure 2. a) Deep water Chlorophyll *a* (Chl *a*) image for February 2012 derived from SNPP VIIRS. b) Deep water Chlorophyll *a* (Chl *a*) image for February 2012 derived from MODIS Aqua. c) Comparison of SNPP VIIRS, MODIS Aqua, and SeaWiFS climatologic mean 8-day composite deep water mean Chl *a* concentration from January 2012 to October 2014. (Figure 3c courtesy of K. Turpie, University of Maryland Baltimore County (UMBC))

In this figure, the agreement between the sensors is quite good and will likely improve as additional vicarious calibration data and instrument radiometric calibration knowledge are accumulated. The images in this figure show that MODIS Aqua and VIIRS are producing derived geophysical properties that are consistent in geographic distribution with similar dynamic range. The plot in this figure represents time-series of aerial averages taken over weekly composites of MODIS Aqua, SNPP VIIRS, and SeaWiFS climatologic data projected onto a 9 km equal area grid. The SeaWiFS climatology composites include data for the corresponding week for all years of the SeaWiFS mission. These satellite data are all processed using the NASA OBPG algorithm and calibration methodologies with the VIIRS data resulting from the OBPG's R2014.0 reprocessing.

Figures 3a and b provide a comparison of total column ozone concentration and Antarctic ozone hole area derived from the SNPP OMPS and the OMI on the NASA EOS Aura satellite, respectively, from August to December 2014. These comparisons were performed by the NASA Ozone PEATE and members of the NASA SNPP Science Team using heritage NASA processing techniques and algorithms. Also shown in Figure 3c is the image of the Antarctic ozone hole on September 30, 2014, the day on which total column ozone was at its minimum. As seen in the plots, the agreement between OMPS and OMI are excellent.

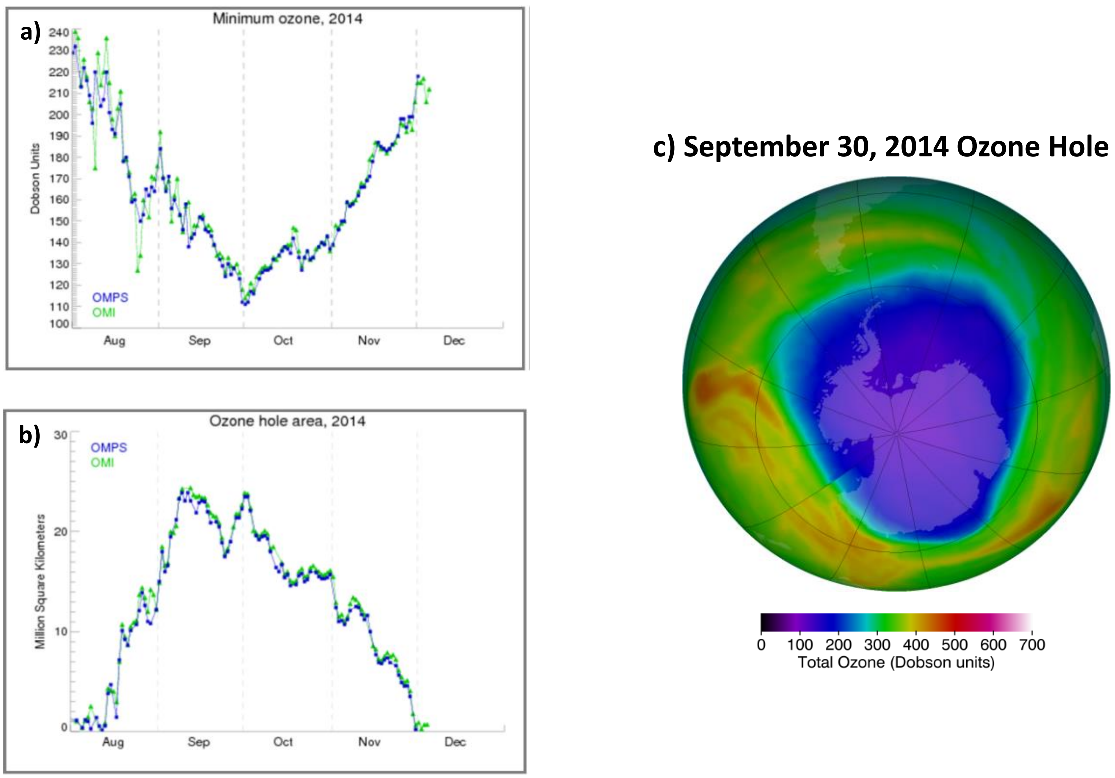

Figure 3. a) Comparison of Antarctic total column ozone concentration from August to December 2014 derived from SNPP OMPS and NASA OMI on EOS Aura. b) Comparison of Antarctive ozone hole area from August to December 2014 derived from SNPP OMPS and NASA OMI on EOS Aura. c) Image of the Antarctic ozone hole on September 30, 2014, the day of minimum ozone concentration. (Figures 2 a) and b) courtesy of C. Seftor, Science Systems and Applications, Incorporated (SSAI))

Figure 4 presents a comparison of skin surface temperature derived from AIRS on the NASA EOS Aqua satellite (i.e. Figure 4a) and SNPP CrIS (i.e. Figure 4b) on December 4, 2013. Skin surface temperature was determined by the Sounder PEATE and members of the SNPP Science Team for AIRS and CrIS using the AIRS version 6.13 algorithm and an AIRS-like version of that same algorithm, respectively. The derived CrIS Version 6.13 skin surface temperatures match those of AIRS very well in terms of yield and accuracy. Figure 4c and 4d show global images of the difference in CrIS and AIRS skin surface temperatures for both the 1:30 pm ascending (i.e. daytime) and 1:30 am descending (i.e. nighttime) portions of the SNPP and Aqua orbits.

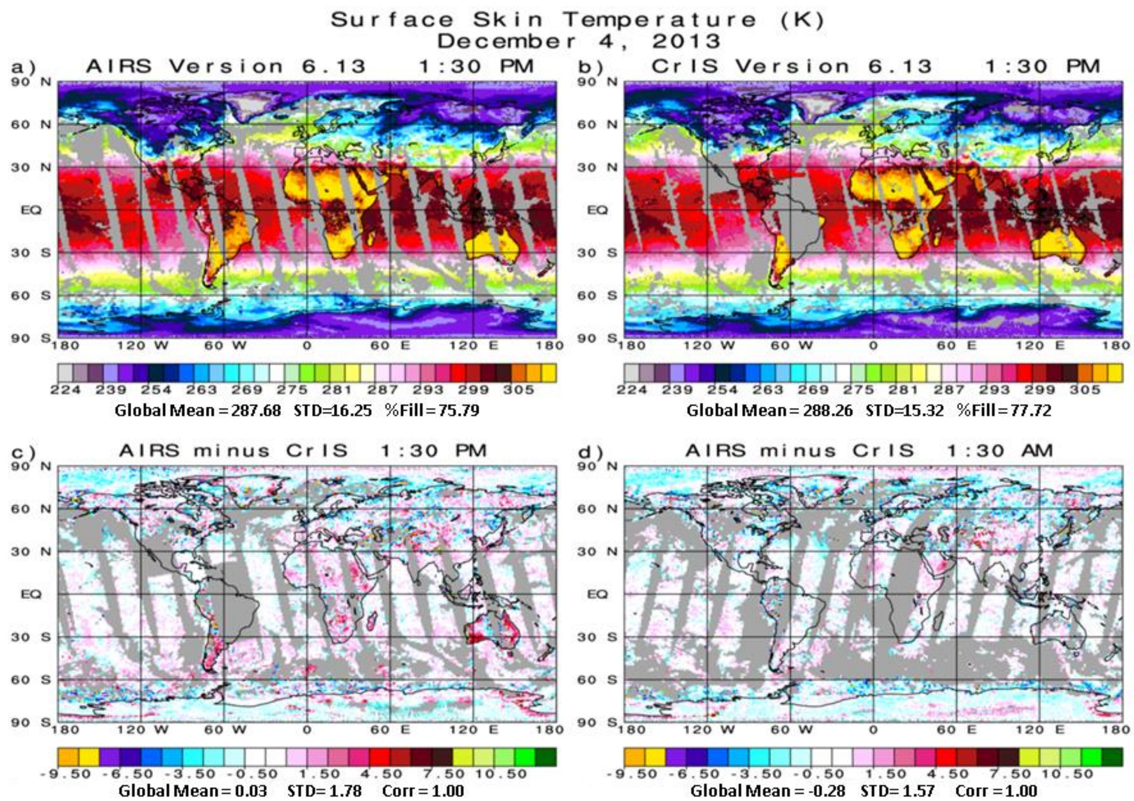

Figure 4. Comparison of skin surface temperature derived from the Atmospheric Infrared Sounder (AIRS) on the NASA EOS Aqua satellite (i.e. Figure 4a) and SNPP CrIS (i.e. Figure 4b) on December 4, 2013. Skin surface temperature differences between AIRS and CrIS on the daytime (i.e. Figure 4c) and nightime (i.e. Figure 3d) portions of the SNPP and EOS Aqua orbits, respectively.

In response to the findings and recommendations within the NASA Science Team Discipline Reports, NASA, in late 2013, directed the SNPP Science Team to use SNPP instrument data to develop data products of sufficiently high quality to enable continuation of EOS time series data records and to develop and demostrate innovative, practical applications of SNPP data. The data records of highest priority were identified in the NASA 2013 SNPP Science Team solicitation and are provided in Table 2. NASA identified the development of new science data products from SNPP data as a secondary priority.

The SNPP science team transition from assessing the quality and suitability of SNPP operational xDRs for NASA Earth science to actually producing science products to continue EOS data records necessitated the establishment of full data processing and production facilities. To do this, the PEATEs, which served as NASA's SNPP data product testing environments during the prelaunch and early on-orbit periods, were transitioned to Science Investigator-led Processing Systems (SIPS). The SIPS are located at the following institutions: the Ocean SIPS at NASA Goddard Space Flight Center (GSFC), the Sounder SIPS at NASA Jet Propulsion Laboratory (JPL), the Atmosphere SIPS at the University of Wisconsin, the Land SIPS at NASA GSFC, and the Ozone SIPS at NASA GSFC. NASA LaRC continues to host the Earth Radiation

Table 2. NASA SNPP Science Products Mapped to SIPS

- Land SIPS
  - Surface Reflectance
  - Snow Cover
  - Land Surface Temperature and Emissivity
  - Land Cover and Dynamics
  - Vegetation Indices
  - Fire and Thermal Anomalies
  - Leaf Area Index
  - Fraction Absorbed Photosynthetically Active Radiation
  - Sea Ice Cover & Ice Surface Temperature
  - BRDF/Albedo
  - Vegetation Continuous Fields
  - Burned Area
- Ozone SIPS
  - Total Column Ozone
  - Ozone Vertical Profiles
  - Aerosol Vertical Profiles
  - NO_2 Total Column
  - SO_2 Total Column
  - Aerosol Total Column
- Ocean SIPS
  - Sea Surface Temperature
  - Aerosol Angstrom Exponent
  - Aerosol Optical Thickness
  - Subsurface Chlorophyll a Concentration
  - Diffuse Attenuation at 490nm
  - Photosynthetically Available Radiation
  - Particulate Organic Carbon
  - Particulate Inorganic Carbon
  - Remote Sensing Reflectance
- Atmosphere SIPS
  - Aerosol Product
  - Total Precipitable Water (Water Vapor)
  - Cloud Product
  - Atmosphere Water Vapor Profiles
  - Atmosphere Gridded Product
- Sounder SIPS
  - Atmopsheric Temperature Profiles
  - Atmospheric Moisture Profiles
  - Atmospheric Pressure Profiles
  - Surface Temperature
  - Cloud Properties

Budget CARS for the processing of SNPP CERES data. The new SNPP distributed data system containing the SIPS is shown in Figure 2. The SIPS acquire SNPP instrument Level 0 (i.e. RDRs) data over the full SNPP mission from the NOAA ADS/CLASS and the IDPS through the SDS Data Distribution and Depository Element (SD3E). The SIPS process those data into level 1 (i.e. SDR), Level 2 (i.e. EDR) and global, gridded Level 3 standard products using peer-reviewed algorithms provided by members of the NASA SNPP Science Team. The SIPS produce these products with metadata in the approved NASA standard format while also performing data quality assessment functions. The SIPS work with the SNPP Science Team in obtaining enhanced, refined, or alternate real-time algorithms to support the capabilities of the Direct Readout Laboratory (DRL). Finally, all data products, algorithm source codes, coefficients and ancillary data used in product generation are archived in an assigned NASA Distributed Active Archive Center (DAAC).

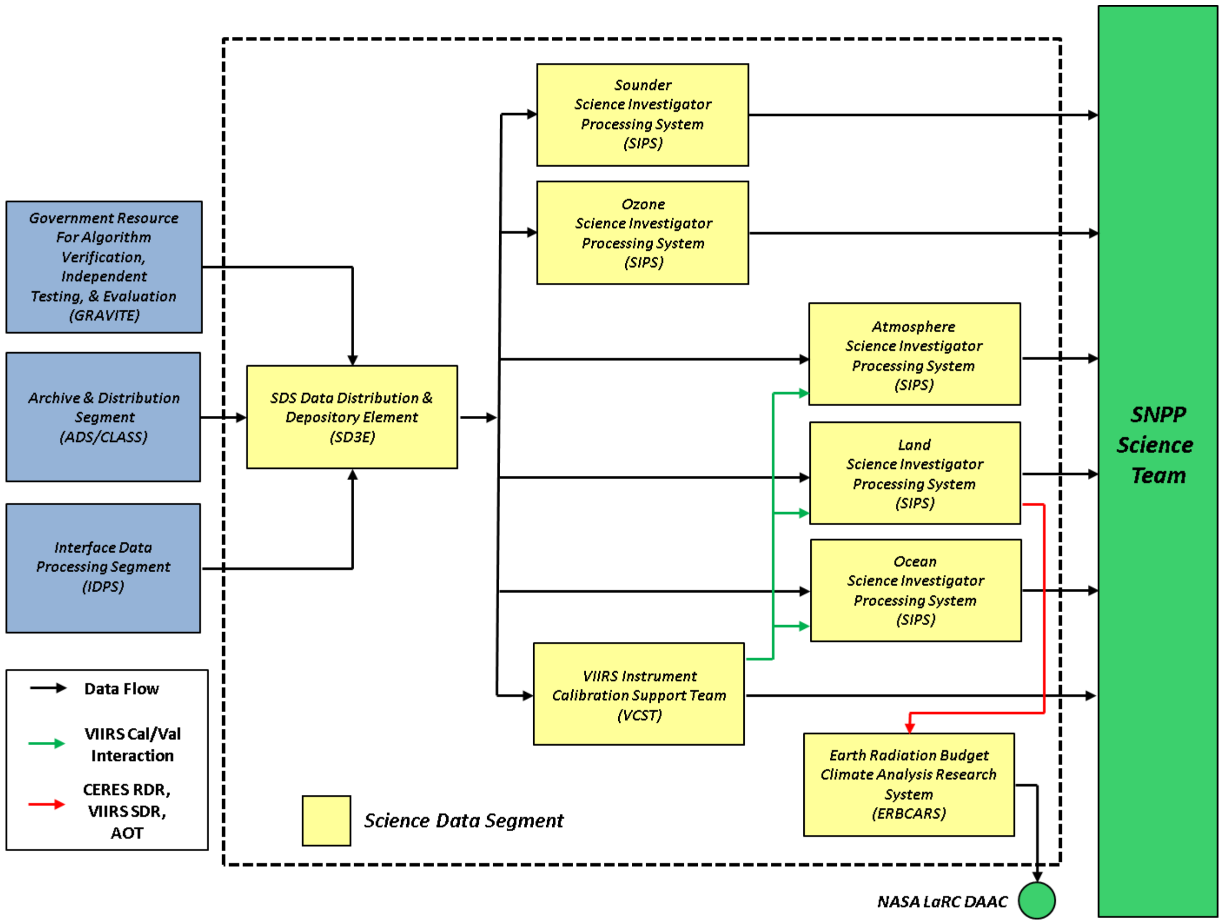

Figure 5. Data flow for the new NASA SNPP distributed data system.

3. SNPP Direct Readout System for Real-Time Applications

The ultimate goal of the direct broadcast (DB) or network-based remote sensing data user is to arrive at an understanding of regional environment dynamics and derive information for decision support. Therefore the extent of Direct Readout's (DR) utility is directly proportional to the ability of the user to provide the derived information to a decision-making infrastructure; whether it is a large farmer assessing a fungal infestation or the federal government assessing damage extent of a tornado. Both require a mechanism or path for real-time DR products to reach appropriate decision-making bodies.

NASA, as a science research organization, has developed space-borne remote sensing instruments and corresponding science algorithms to measure and quantify geophysical parameters for use in understanding and quantifying climate change. Many of these algorithms, as described in the above sections for use on a global and longer temporal scale, are applicable for real-time regional applications. These applications, as further described in Section 4 with recommendations and examples, are the driving force behind the porting of specific science algorithms to real-time DR application algorithms. The latest, updated ported science algorithms and support technologies designed to function in a DR environment for direct use by application users are freely available for download at http://directreadout.sci.gsfc.nasa.gov.

Through the use of near-real-time data obtained from internet-based data centers and from DB on EOS and SNPP satellites, real-time environmental data is made available on a continuous basis world-wide for ready data processing given three elements necessary to render useful products by the general application user: instrument specific algorithms along with data processing tools to handle a live data stream, data product formatting or data transport tools, and product distribution mechanisms for decision support systems enabling the use of space-borne remote sensing data for real-time applications.

The NASA DR model has identified key technology categories that the DR end-user would have to contend with in order to be compliant with a multi-satellite and multi-instrument environment. These categories include: real-time system processing tools (i.e. the International Polar-Orbiting Processing Package (IPOPP)), Consultative Committee for Space Data Systems (CCSDS) packet re-assembly and standard data reformatting tools (i.e. Real-Time Software Telemetry Processing System (RT-STPS)) and Hierarchical Data Format (HDF) to GeoTiFF (H2G)), instrument-specific calibration and geo-registration algorithms, a science processing algorithm (SPA) wrapping schema for standard system integration and sustainment, and real-time data distribution mechanisms (Simulcast). NASA has addressed these key technology categories in the form of specific technologies which are generic in nature and can be integrated into existing or developing DR systems.

a. International Polar-Orbit Processing Package (IPOPP)

The IPOPP is the primary element that addresses the technology needs to enable the real-time DR community to process, visualize, and evaluate EOS and S-NPP sensor data. IPOPP is available for download at: http://directreadout.sci.gsfc.nasa.gov/?id=software. The principle purpose of the IPOPP is to host Science Processing Algorithms (SPA). IPOPP system elements are illustrated in Figure 6.

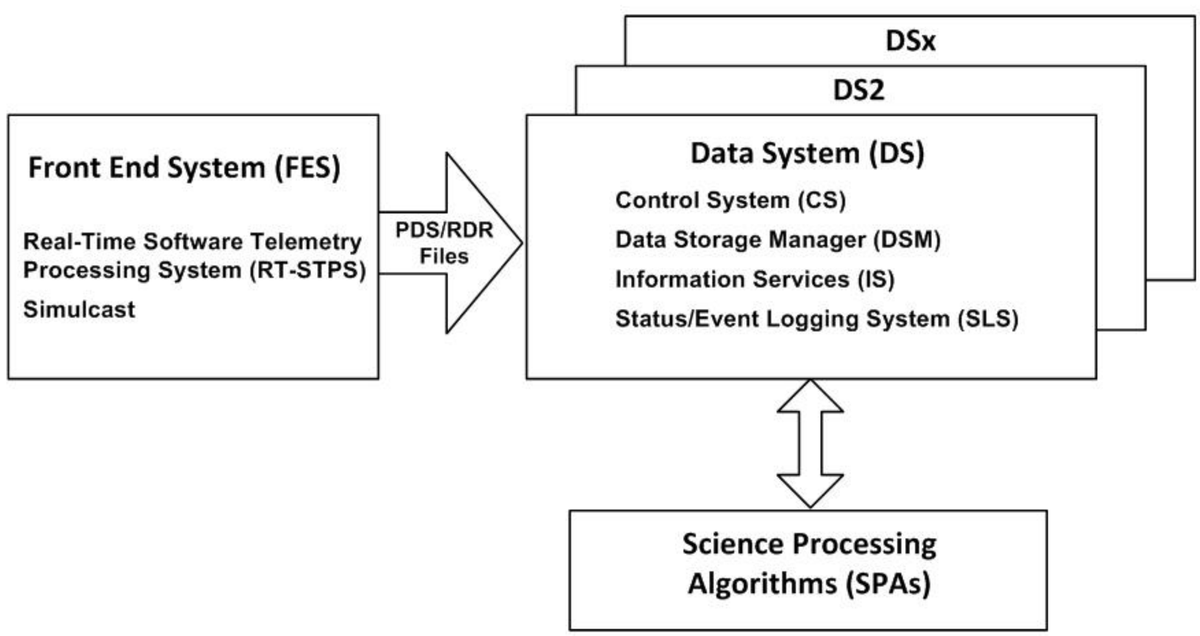

Figure 6. IPOPP Framework for real-time Earth science Data Processing

Beyond the processing needs of the broader DR community, the IPOPP is used as a DR application's algorithm evaluation tool for collaborators. The generalized architecture is an excellent basis for algorithm evaluations; a heterogeneous implementation where the core resource management is verbose and easily referenced yielding ambiguity mitigation when performing detailed product intercomparisons.

b. Science Processing Algorithm (SPA) Architecture

The SPA wrapper is key to the modular, real-time Earth data processing approach. Algorithm wrappers provide a common command and execution interface to encapsulate multi-discipline, multi-mission SPAs as described in Figure 7. The wrapper also provides a structured, standardized technique for packaging new or updated algorithms with minimal effort.

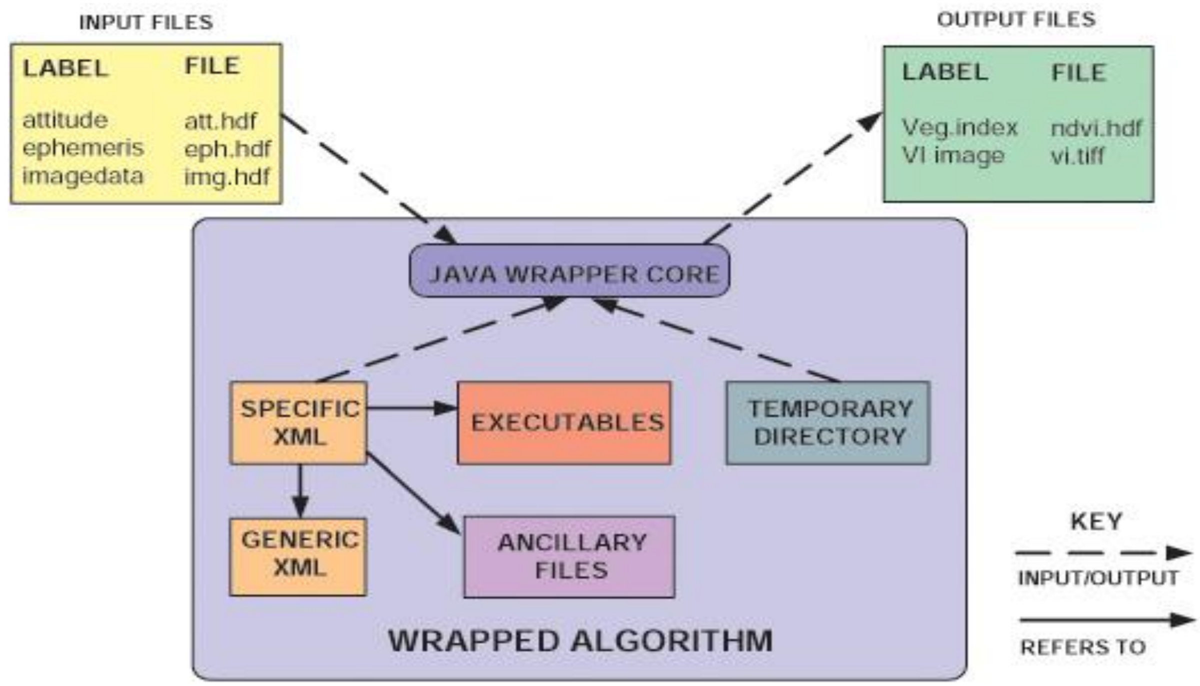

Figure 7. SPA Architecture

Figure 8 illustrates the SPA concept within the IPOPP context. It shows the four functional components for a basic SPA: Core algorithm, a single Wrapper, a single Station and a single Ancillary Retriever. Complex SPAs may have multiple Stations, Wrappers or Ancillary Retrievers, but the basic relationship between these components and how they interface with each other remain the same.

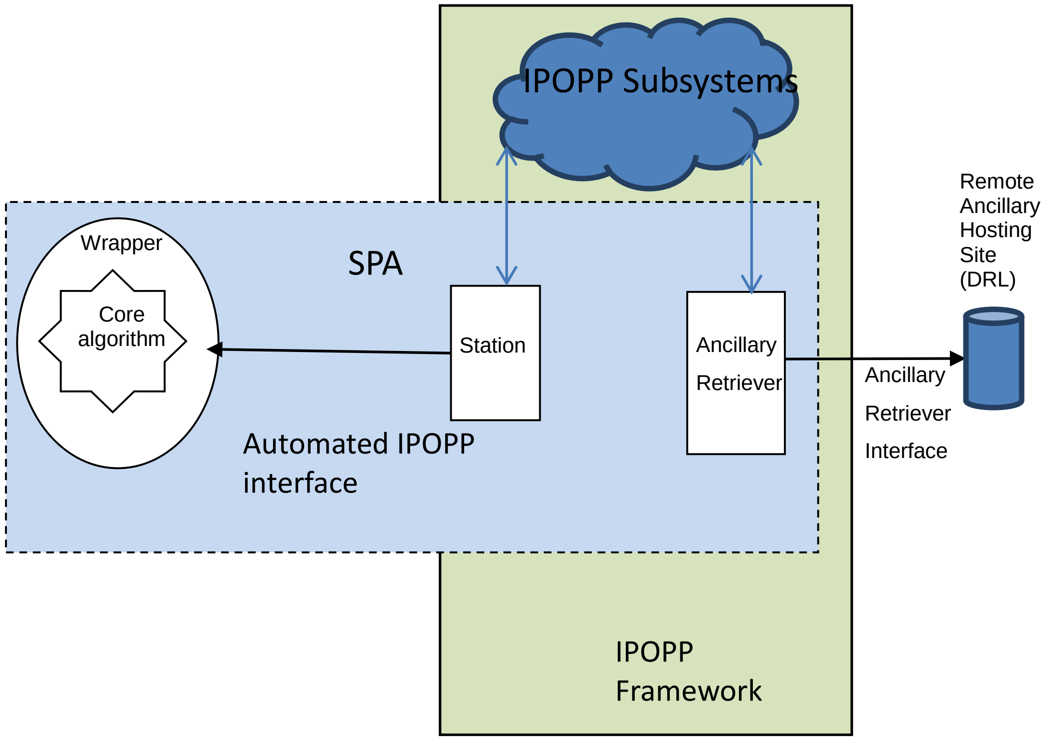

Figure 8. Science Processing Algorithm Architecture within IPOPP Implementation

c. *Real-Time Software Telemetry Processing System (RT-STPS)*

The RT-STPS is a front-end element into IPOPP. It ingests raw CCSDS-compliant data units that may be Pseudo-noise (PN)-encoded or Reed-Solomon (RS)-encoded and outputs Virtual Channel Data Units (VCDUs) or packets into the following formats:

- RDR files: Suomi NPP VIIRS, ATMS, CrIS, MODIS, AMSR-E, AIRS;
- Production Data Set (PDS) (packet file and Construction Record [CSR]) file pairs;
- File: header, trailer and no annotation;
- Sockets.

RT-STPS functions in two modes: Standalone, or as an IPOPP plug-in. Installed as a server RT-STPS will operate continuously, receiving data from a port or a file and outputting results to files and sockets as specified in a configuration file. A separate interface can be used to invoke RT-STPS from the command line.

The RT-STPS package includes two main utilities: the viewer and the sender. The viewer displays the progress of the server as it runs, and it can be used to load server configuration files. The sender copies a raw data file to the server for processing. RT-STPS is available for download at: http://directreadout.sci.gsfc.nasa.gov/

d. Simulcast

Simulcast is a real-time Java application that allows users to select and view quicklook instrument data from multiple missions and spacecraft locally or remotely. Simulcast specifically addresses the need to view imagery in real-time no matter where the user is located so long as an internet connection of 128 Kbps and above is available. Simulcast provides real-time geolocation and pseudo-calibration, and projects data on Mercator and Polar maps. Simulcast can replay recent satellite passes, export displayed images to JPEG format, and save replayed passes to AVI/Quicktime movies. Simulcast functions in two modes: Standalone or as an IPOPP plug-in.

The Simulcast Client consists of the Simulcast Viewer and the Simulcast Console. The Viewer displays data from satellite passes (VIIRS data from S-NPP, and MODIS data from Aqua and Terra) as seen in Figure 9. The Console displays and controls administrative information. Before data can be displayed with the Viewer, the data must first be acquired, routed and processed by Simulcast Services. Simulcast Services contains the Simulcast Router, Processor, and Server.

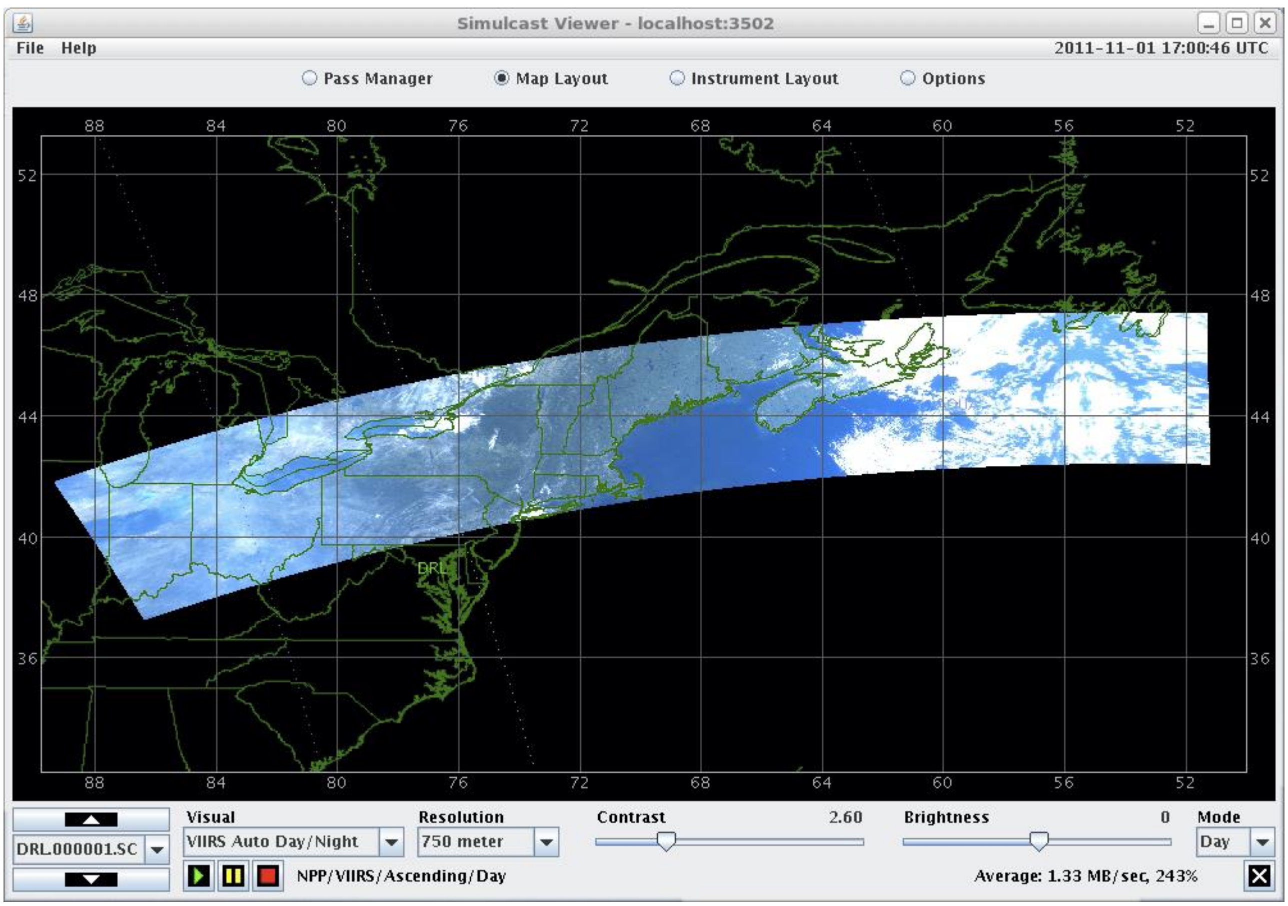

Figure 9. Simulcast Real-Time Viewer Interface

When a pass starts, the Router receives the CCSDS packet stream from the RT-STPS and transmits the packets to one or more Processors. The Router filters the packets by instrument type.

The Processor receives the filtered packets from the Router and extracts instrument data. The Processor calibrates the data, corrects the bow tie effect, and reduces data volume. The Processor transmits viewable data to the Server. The Server receives viewable data from the Processor and notifies Clients that the new pass data are available. The Server simultaneously stores the data locally (for possible replay later) and transmits it to Clients and other Servers. A Server can handle connections from multiple clients simultaneously, with each Client either receiving the data from the current pass or from a previous pass**.**

e. Application Science Algorithms

Once real-time data are made possible on the spacecraft or through an IP network, the second, equally as important component needs to be addressed, the application science algorithms. These provide, at a minimum, scientifically valid baseline products of geophysical parameters that can be of regional utility.

Within NASA's EOS missions, S-NPP, and JPSS-1, significant efforts have been made to develop science products that would stand the scrutiny of global change studies as described in the above section. These science algorithms are supported by extensive calibration and validation campaigns pre- and post-launch which have supported the now continuous update to these algorithms and enabled accurate data and sensor continuity measurements.

The most important algorithms for the DR community have been for their use with the MODIS instruments on the EOS Terra and Aqua spacecraft and the VIIRS instrument on S-NPP. These instruments, with their support science algorithms, provide geophysical parameters that are of high utility to the global community. But with any science quality algorithm there has to be a process by which to validate the ported, wrapped algorithm that is to be used in a DR environment. The porting process is necessary and is defined as the process of making necessary environmental algorithm changes/additions so as to allow such algorithm to function in a real-time, DR environment, where system infrastructure-based dependencies are removed and/or emulated, variable data blocks are the norm, and variable ancillary/auxiliary data sources and conversions may exist. Once porting is complete the algorithm is supported by the SPA wrapper which provides a run-time interface standard and all the hooks and functions necessary for the DR user to incorporate such an SPA into their existing processing chain or the IPOPP.

Currently available VIIRS, ATMS and CrIS instrument SPAs are listed in Table 3.

Table 3. VIIRS, ATMS, and CrIS Instrument SPAs

• VIIRS RDR and SDR	•Cloud Top Temperature	•Sea Ice Characterization
•Aerosol Optical Thickness (AOT)	•Ice Surface Temperature	•Surface Albedo
•Cloud Base Height	•Imagery Band I1-I5	•Suspended Matter
•Cloud Effective Particle Size	•Imagery Band M1-M16	•Vegetation Index
•Cloud Optical Thickness	•Land Surface Temperature	•CrIMSS RDR, SDR, and EDR
•Cloud Top Height	•Near Constant Contrast Imagery	•ATMS RDR and SDR
•Cloud Top Pressure		

Additional algorithms are available under the H2G SPA tool (below) which includes support for:

- VIIRS Snow Cover Fraction;
- compressed SNPP data products;
- color maps and color scales in OMPS images;

- ATMS SDR Brightness Temperature, CrIS SDR Brightness Temperature and VIIRS SDR Reflectance and Brightness Temperature image generation capabilities (in Standalone Mode only until the next release of IPOPP);
- inverse distance-weighted interpolation and image smoothing technique for ATMS SDR, CrIS SDR and OMPS image products;
- browse product option to produce image products with improved legends and latitude/longitude overlays;
- vector overlays in Polar Stereographic projection.

f. Product Transport Mechanism - HDF to GeoTIFF (H2G)

Most real-time applications make use of a Geographic Information System (GIS) that brings together various pieces of information and presents them in a way that allows for the user to accurately gauge environmental impact. GIS remains one of the most important tools for analyzing NASA's EOS data and promoting real-time applications. GeoTIFF is one of the GIS-ingestible formats; and, therefore, the ability to produce GeoTIFF from HDF-EOS and HDF-5, will greatly enhance the interoperability and public use of EOS/JPSS data. The availability of GIS-ready products will improve data analysis and visualization and promote the use of such data not only in global change research but also in the public who is concerned with issues such as environment and resource management, hazard mitigation, education, and community planning.

A primary step in making this happen is to enrich the GeoTIFF format with the necessary metadata. Geospatial metadata have been recognized for playing four roles: (i) Availability: metadata needed to determine the sets of data that exist for a geographic location, (ii) Fitness for use: metadata needed to understand how the data was acquired and processed (lineage) to determine if a set of data meets a specific need, (iii) Access: metadata needed to acquire an identified set of data, and (iv) Transfer: metadata needed to process and use a set of data. Apart from these four obvious uses, metadata can be an important component in triggering future research and development by means of a feedback mechanism. As users analyze the lineage metadata associated with a dataset, they may identify processes that may have degraded the data quality and discover alternate techniques that could potentially improve the data quality and make it suitable for a particular application.

A prime example of metadata enhancement is the incorporation of standard color tables within the GeoTIFF meta-data fields. Such tables would be helpful in promoting uniformity in visualizations of a particular geophysical parameter. Over the years researchers have associated each EOS product with a color map that best represents the parameter described in the product. This would ensure that the user has access to the standard color scale used for the product. The user however will have the flexibility to change the color scale within the GIS platform for further analysis. When producing GeoTIFF products we must ensure that the encoded color map is the standard color map representative of the geophysical parameter.

In order to address the required GeoTIFF meta-data enhancements NASA has developed and is making available the H2G_SPA (HDF to Georeferenced Tagged Image File Format [GeoTIFF] Converter Science Processing Algorithm). H2G_SPA is specially designed for near-real-time processing and to create geolocated GeoTIFF images, jpeg browse images, and png browse images for various parameter datasets in SNPP SPA and MODIS Level 2 SPA products. H2G also creates standard true color images and user-defined false color images from supported VIIRS and MODIS science products. The H2G_SPA functions in two modes: Standalone or as an IPOPP plug-in.

4. NASA SNPP Data Applications

In 2014, NASA held the Second Suomi NPP Applications Workshop to brief application users on upcoming data products, and to exchange information between application developers, the NASA Science Team, and the new Science Investigator-led Processing Systems (SIPS) community. The workshop provided updated information on instrument performance, data characteristics, and ways to access the data, a review of current Suomi NPP applications in use by end users, and an opportunity for community to provide feedback to NASA and the science team, and an effort to identify current barriers to the integration of Suomi NPP data into other existing and developing applications. Much of the interaction was conducted in breakout sessions aligned with the four focus areas of Public Health and Air Quality, Water Resources, Ecological Forecasting, and Disasters. Leaders of each breakout session received input and participated in discussions focused on a list of questions that was provided to workshop attendees.

The breakout participants for the Disaster focus area identified a variety of partners and end users of Suomi NPP data for disaster applications including federal, state, and local agencies responsible for emergency management, Non-Governmental Organizations (NGOs) including the Red Cross and World Bank, international groups focused on remote sensing (Group on Earth Observations (GEO), Committee on Earth Observation Satellites (CEOS) and pilots), capacity building groups (SERVIR), and research-to-operations organizations (SPoRT). The end users accessed a combination of SNPP data and products with other satellite data missions (e.g. synthetic aperture radar) and field campaign data, volcanic gas composition including SO_2 and ash, flood-relevant data for modeling and forecasting, land surface products for identifying surface water, burn scars, and sudden change (surface reflectance, cloud masking, surface emissivity and land surface temperature, precipitation and snowfall) in their use of the data. Fire-relevant data and products such as hot spot detection and the VIIRS day-night band, along with smoke detection and monitoring (overlapping with Public Health/Air Quality needs) were also utilized. A variety of improved or new products were discussed to facilitate greater utilization of the data including the removal of striping, stray light contamination, and providing terrain-corrected geolocation consistent with other VIIRS bands, cloud masking, and attribution of lights to varying sources. It was suggested that data latency should be reduced whenever possible to improve response time in disaster applications. The VIIRS Day Night Band (DNB) requires additional work to produce standardized products (e.g. standardized reflectance in addition to radiance, attribution of light sources, higher-level composites and other products similar to other land surface data sets). There was a specific request to increase the spatial resolution of OMPS volcanic ash and SO_2 measurements from 50 km^2 to 12-17 km^2. VIIRS lacks a series of water vapor bands but similar information could be mapped to VIIRS spatial resolution from the CrIS instrument. Icing products for aviation could support the Federal Aviation Administration and transportation safety. Land type and use classification can aid in disaster response by identifying sudden changes in surface characteristics resulting from storm damage and fires, or mapping of flood extent.

The breakout participants for the Public Health and Air Quality focus area identified the U.S. Centers for Disease Control and coordination with state/local health departments (18 states funded by climate health program), Environmental Protection Agency and their local/state counterparts, the NASA Air Quality Applied Sciences Team (AQAST), African decision-makers and universities, Brazil, Latin American, and Asia MOHs, NOAA, United Nations health organizations (WHO, FAO, etc.), Department of Defense (NAMRU, NRL), GEO and GEOSS in the Americas as current end users of SNPP data. Future partners could include the ECMWF, partnerships on wildfire detection, private industry and drug companies, the World Bank, and non-governmental organizations or other boundary organizations (e.g. Gates or Heinz Foundations, IANPHI, etc.). Past activities that have been developed for and focused on vector borne diseases from MODIS and use of VIIRS would be a natural extension for water bodies, temperature, and vegetation. Trace gases and aerosol data are used in analyses and data assimilation. It was suggested that contributions of Suomi NPP data and linkage to socioeconomic data (e.g. CIESEN at Columbia University) could be used to elucidate what is occurring on the ground. Monitoring of ozone and stratospheric ozone intrusions is useful for EPA extraordinary event documentation. There is interest in continuing the mid-tropospheric CO_2 product from AIRS with CrIS for atmospheric circulation studies. Terra and Aqua products used include soundings and atmospheric composition, AIRS ozone, MODIS products for data assimilation, Level 2 products with cloud clearing (under development for VIIRS), OMI total column ozone, ozone from the Microwave Limb Sounder (MLS) and the Tropospheric Emission Spectrometer (TES), MODIS land surface temperature, aerosol optical depth, and normalized difference vegetation index. Additional relevant Suomi NPP products include VIIRS DNB composite data, desiring monthly cloud-filtered/cleared data sets to see trends, use of VIIRS in data assimilation studies, OMPS total column ozone, NO_2 and SO_2, CrIS ozone, and aerosol optical depth. Users requested that additional SNPP products be made available through LANCE or other near real-time data distribution services, particularly for EOS era products extended by SNPP observations. Currently, near real-time VIIRS access is limited to PEATE/SIPS or direct broadcast, CrIS through CLASS subscriptions that can be intermittent (or PEATE), and OMPS data access is limited to PEATE. Participants said that as a first consideration, look to NOAA and whether they are producing something adequate for the user community. This will help identify gaps that can be filled by NASA. The community would like to see additional flexibility to create their own higher level products. Full spectral resolution of CrIS data are needed to perform CO retrievals, and averaging kernel information from CrIS is required to determine the degrees of freedom There is a request to improve the NO_2 and SO_2 monitoring and volcano detection capabilities from OMPS by improving the product spatial resolution to 12 km (currently 50 km).

In the water resources focus area, workshop participants identified NOAA and the National Weather Service, operational forecast centers, NESDIS, international meteorological services, United States Department of Agriculture, National Drought Mitigation Center, NIDIS, California Department of Water Resources, United States Geological Survey, National Snow and Ice Data Center, National Geospatial Intelligence Agency, Ministries of Environment / Agriculture / Mapping, U.S. Agency for International Development, SERVIR hubs, EarthTemp and Glob Temp international collaborations for monitoring land surface temperature, United Nations, non-governmental organizations, climate modelers, and hydrologic modelers as users of SNPP data. These groups focus on drought monitoring, water quality (including freshwater, coastal, inland bodies, and agricultural runoff), harmful algal blooms, flood monitoring and forecasting, water supply monitoring and forecasting, land degradation and desertification, water rights monitoring and compliance, water budget and hydrologic cycle studies, soil moisture, thermal pollution (e.g. industrial or power station discharge plumes), coral bleaching, reef monitoring, ocean acidification, and hypoxia problems. Several products are used from MODIS and VIIRS, including surface reflectance, albedo, vegetation indices and top of atmosphere derived green vegetation fraction, sea ice extent and surface temperature, snow cover, cloud masking, water-leaving radiance, sea surface temperature, chlorophyll-a, measurements of turbidity (K_d 490), and photosynthetically active radiation. MODIS-only applications include land surface temperature and emissivity, leaf area index, top of canopy vegetation indices, evapotranspiration, chlorophyll fluorescence, and land cover. Numerous additional products from SNPP mission data would be beneficial, such as evapotranspiration measurements, leaf area index, photosyntetically active radiation, water use efficiency, land cover, green vegetation fraction, precipitation rate, and vertical profiles of absorbing aerosols. A land surface temperature and emissivity product is desired from VIIRS, along with improvements in the cloud masking capability, especially at night when there may be difficulty discriminating clouds from snow. Green vegetation fraction and leaf area index could be daily, shorter latency requested for other products. Also, the community requests salinity measures for coastal water, which can be derived from ocean color.

The breakout participants for the ecological forecasting focus area share similar goals to the water resources focus area. The focus area participants identified the National Ocean Science group, NCEP, National Marine Fisheries, NOAA NESDIS, National Estuarine Research Reserves, NEP, conservation organizations (e.g. U.S. Forest Service, Conservation International, Global Forest Watch), United Nations Food and Agriculture, NOAA NCDC and Fisheries Science Centers, and CDC-EPHT as current users of SNPP data. These end users desire to use SNPP data to address coastal and inland water quality, agriculture monitoring and prediction, and other environmental modeling and monitoring applications. The end users identified data from Terra and Aqua, particularly chlorophyll-a, Kd 490, sea surface temperature, photosynthetically active radiation, vegetation indices, land cover and land use change, land surface temperature, and reflectances used in deriving coastal salinity properties as key parameters to be derived from SNPP data. Additional products of interest include lidar-absorbing aerosol and vertical profile in coastal regions for the calibration of other data, measurements of coastal salinity, and products at resolution of 750-300 m or less. A coastal-observing geostationary source would be of particular interest. Many products remain in a test phase due to ongoing calibration issues, and these must be resolved in order to move forward on application development. There is a need for additional MODIS and VIIRS overlapping product generation to ease the transition to a new data set and series of input products. There are some dual NASA and NOAA products, and steps should be taken to ascertain which is better for given applications.

The participants in all breakout sessions shared some common concerns that limit the use of SNPP data for current and new applications. Many felt that the community still does not know to go to NASA for observations, data, and models supporting applications in the focus areas. Even if data products are provided, users lack sufficient training and expertise for incorporating and using them in their decision-making process.   Participants sought a “one-stop shop” for data and applications that are developed from Level 1, Level 2, or Level 3 data products. Currently, NASA DAACs focus on science team outputs, whereas a single portal for application outputs is not yet available.   An applications portal should be developed to provide data in various forms (GeoTIFF, HDF, netCDF, etc) with limited latency and tools for search, reprojection, and subsetting. SNPP products should be developed with algorithms and quality assurance flags consistent with predecessor instruments (MODIS, AIRS, etc.).