An Overview of ARM Program Climate Research Facility Data Quality Assurance

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Abstract: We present an overview of key aspects of the Atmospheric Radiation Measurement (ARM) Program Climate Research Facility (ACRF) data quality assurance program. Processes described include instrument deployment and calibration; instrument and facility maintenance; data collection and processing infrastructure; data stream inspection and assessment; problem reporting, review and resolution; data archival, display and distribution; data stream reprocessing; engineering and operations management; and the roles of value-added data processing and targeted field campaigns in specifying data quality and characterizing field measurements. The paper also includes a discussion of recent directions in ACRF data quality assurance. A comprehensive, end-to-end data quality assurance program is essential for producing a high-quality data set from measurements made by automated weather and climate networks. The processes developed during the ARM Program offer a possible framework for use by other instrumentation- and geographically-diverse data collection networks and highlight the myriad aspects that go into producing research-quality data.

1. INTRODUCTION

We overview key aspects of the Atmospheric Radiation Measurement (ARM) Program Climate Research Facility (ACRF) data quality assurance program as of 2008. The performance of ACRF instruments, sites, and data systems is measured in terms of the *availability, usability,* and *accessibility* of the data to a user. First, the data must be *available* to users; that is, the data must be collected by instrument systems, processed, and delivered to a central repository in a timely manner. Second, the data must be *usable*; that is, the data must be inspected and deemed of sufficient quality for scientific research purposes, and data users must be able to

readily tell where there are known problems in the data. Finally, the data must be *accessible*; that is, data users must be able to easily find and obtain the data they need from the central repository, and must be able to easily work with them.

The processes highlighted here include instrument deployment and calibration; instrument and site maintenance; data collection and processing infrastructure; data stream inspection and assessment; problem reporting, review and resolution; data archival, display and distribution; data stream reprocessing; engineering and operations management; and the roles that value-added data processing and field campaigns have played in specifying data quality and characterizing basic measurement. Recent directions in ACRF data quality assurance are outlined near the end of this article. Greater detail and background on some of these processes can be found in [1]. The programmatic and scien-

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tific objectives of the ARM Program, designed to improve our understanding of the processes that affect atmospheric radiation and the characterization of these processes in climate models, and of the ACRF measurement sites, situated to provide an accurate description of atmospheric radiation and its interaction with clouds and cloud processes, can be found in [2] and also online at http://www.arm.gov/. A ten-year retrospective of the program's scientific and observational thrusts and achievements up to 2003 is provided in [3].

2. BACKGROUND

The value of any geophysical measurement is dependent on the accuracy and precision with which it represents the physical quantity being measured. Factors such as instrument calibration, long-term field exposure to the elements, and instrument maintenance all play a role in collecting what ultimately becomes a good or bad data set. To be most useful for scientific research purposes, a comprehensive, end-to-end quality assurance program, from instrument siting, to calibration and maintenance, through continuous data quality evaluation and well-documented dissemination, is essential.

The attention paid to data quality assurance in the recent (since 1990) peer-reviewed meteorological literature attests to these concerns. The quality assurance of major automated data collection networks has been described for the Baseline Surface Radiation Network [4], Oklahoma Mesonet [5], Surface Radiation Budget Network (SURFRAD) [6], and the West Texas Mesonet [7]. Specific aspects of quality assurance for automated networks have been documented on standards and best practices for automated weather stations [8]; screening rules for hourly and daily data values from individual stations [9]; the importance of site characterization and documentation [10]; variation in characteristics of mesonets, their meteorological implications, and the need for the establishment of standards [11]; impacts of unique meteorological events on automated quality assurance systems [12]; the value of a dedicated quality assurance meteorologist [13]; the importance of weather station metadata [14]; and the value of routine preventative instrument and site maintenance, equipment rotation, and vegetation control [15].

Other recent work has focused on quality assurance of data from particular instruments, including, for example, quality control of profiler measurements of winds and radar acoustic sounding system temperatures for the U.S. National Oceanic and Atmospheric Administration Wind Profiler Demonstration Network [16]; calibration of humidity and temperature sensors for the Oklahoma Mesonet [17]; limitations of sensors used to measure skin temperature in the Oklahoma Mesonet [18]; data quality of 915-MHz wind profilers operated by the U.S. Air Force [19]; development of techniques for improving the relative accuracy of longwave radiation measurements made by pyrgeometers during the Cooperative Atmosphere-Surface Exchange Study (CASES-99) experiment [20]; and monitoring of soil moisture across the Oklahoma Mesonet [21].

As this work attests, much effort is expended to ensure that collected data are of the highest quality possible, not only for the immediate purposes of the particular network, but also for future data-mining and research endeavors. A recent community workshop sponsored by the U.S. Weather Research Program on the design and development of a multi-functional, comprehensive mesoscale observing system for integrated forecasting efforts has reemphasized the importance of data standards and attention to data quality as key parts of an integrated, end-to-end solution [22].

End-to-end data quality assurance also has been put in practice by the ARM Program since its field inception in 1992. Data collection has taken place at the Southern Great Plains climate research facility since late 1992 [23], at the Tropical Western Pacific facility since 1996 [24], and at the North Slope of Alaska facility since 1997 [25]. Fig. (**1**) displays the locations of the three fixed ACRF sites as well as those of mobile facility deployments through 2008. ACRF sites contain a broad spectrum of instrumentation not routinely seen in weather and climate observing networks (see http://www.arm.gov/instruments/), presenting unique challenges and opportunities with respect to data quality assurance. Also, in 2004, ARM's climate research facility ensemble and its infrastructure were designated a national user facility. Now referred to as the ARM Program Climate Research Facility, or ACRF, it provides data and information not only to meet the immediate science goals of the ARM Program but also to satisfy the needs of the climate science community at large. This has heightened the importance of producing high quality data.

3. INSTRUMENT DEPLOYMENT

ACRF sites consist of numerous instrument platforms that measure solar and terrestrial radiation; wind, temperature, and humidity; soil moisture and thermal profiles; cloud extent and microphysical properties; and atmospheric aerosols (see http://www.arm.gov/measurements/). For the most part, the instruments that make these measurements have been obtained from commercial manufacturers for their mature design, operational reliability, ease of maintenance, availability of spare parts, and cost. Some, however, were research instruments that have been hardened for autonomous, long-term field operation within a funded instrument-development program.

3.1. Role of Instrument Mentors

Each instrument is assigned a "mentor" (see http://www.arm.gov/instruments/mentors.php). Mentors act as the bridge between instrument providers and the measurement needs of the ARM science community. Mentors thus play a key role in selecting and testing instruments and for deploying them in the field. Usually a scientist or engineer, the mentor serves as the technical point of contact for the instrument and is responsible for developing a fundamental statement of baseline expectations for instrument performance. Data quality ultimately depends on how closely a measurement conforms to an expectation; without an expectation, an accurate assessment of quality is not possible. The mentor documents the expected performance in terms of attributes such as accuracy, precision, and response time, so that data users can determine the suitability of the instru-
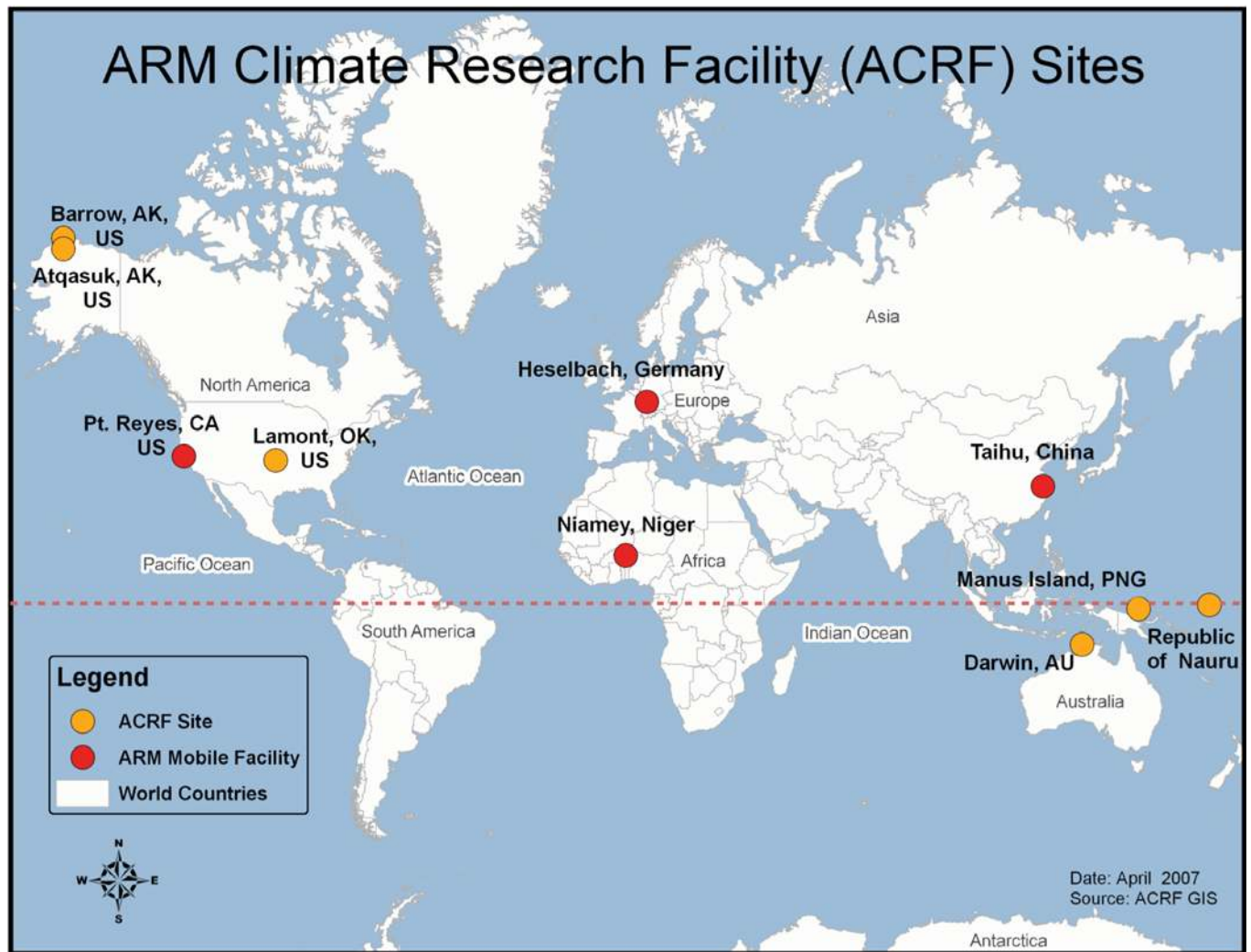
Fig. (1). ARM Program Climate Research Facility measurement locations. Gold markers represent fixed sites while red markers denote mobile facility deployments through 2008 (USA - 2005; Niger - 2006; Germany - 2007; China - 2008).

ment's measurements for their specific application. Such information can be found in an online instrument handbook, which includes information on the current understanding of the instrument's quirks and limitations and a description of common problems that have been encountered or are inherent to its measurements. Ultimately an instrument system is deployed according to ACRF operational and engineering baselines.

The mentor initiates the field deployment process by preparing technical specifications for measurement (in cooperation with relevant ARM Science Team members and other experts). The mentor also participates in the evaluation of technical proposals from prospective suppliers, and carries out acceptance testing to ensure that performance expectations are met. Initial acceptance testing is a contractual action in which the instrument is verified by the mentor to insure the system meets performance specifications. Final acceptance testing is performed by the mentor, a data ingest developer, and site operations personnel as part of a readiness review, which has several parts. This review provides site operators with detailed guidance for field installation and the documentation and training necessary to allow field

technicians to operate, maintain, diagnose, and repair the instruments once in the field. It also provides data system personnel with information needed to collect the data, including the size, naming convention, and frequency of the data files, and a comprehensive description of data fields and supporting metadata to permit ingest and conversion to the self-documenting NetCDF file format. Simple limits checking (minimum value, maximum value, and maximum rate of change, or "delta") are specified by the mentor to be applied during data ingest and the results (flagging) are included in the data file. This review also provides data quality analysts with detailed guidance on how to inspect data and to make an initial assessment of problem cause. Depending on the instrument, a mentor may provide algorithms to data quality analysts that permit more sophisticated checking of the data to identify subtle problems. Finally, the Data Archive is provided with descriptive metadata about the instrument's measurements that allow data users to locate data of interest by their attributes.

Instrument mentors have well-defined responsibilities with respect to ongoing quality assessment. The first involves whether the technical specifications of the instrument

are being met by the initial data collection, and includes an initial evaluation of flagging limits. When the mentor is satisfied that the instrument is functioning properly, the data are formally released to the scientific community. In this role, instrument mentors represent the first line of defense in data quality assessment and problem diagnosis and solution. Routine, near real-time data inspection and assessment is then handed off to data quality analysts, though the mentor serves as the technical consultant to assist the analysts when unexpected or unrecognized problems arise, and figures strongly in problem reporting and resolution. As the technical authority on the instrument, the mentor has the final word on data quality and is responsible for writing data quality reports that are distributed with data to the user community. A mentor also monitors long-term instrument performance characteristics such as subtle trends and documents them in a monthly report. This analysis may necessitate instrument recalibration, modification of maintenance practices, component replacement, or a system upgrade.

3.2. Instrument Calibration

The calibration of instruments before fielding and periodic calibration checks once operational represent crucial components of the quality assurance process. Procedures are developed for each instrument based on manufacturer recommendations but often are adapted by instrument mentors to suit remote operation. Procedures may be as simple as side-by-side comparisons of temperature and humidity conducted during preventative maintenance visits or as complex as laboratory comparisons to known standards. Calibration information and uncertainty estimates are provided in the online instrument handbooks and in a new database described in Section 13.3.

As an example, the ARM Program requires accurate measurement of solar radiation from radiometers used in ground-based networks and airborne instrument platforms. Such measurements are needed to improve the mathematical description of radiative transfer processes simulated in global climate models. In particular, the evaluation of excess solar absorption by clouds is highly dependent on accurate measurements of downwelling solar radiation [26,27].

To meet this measurement need, more than 100 broadband shortwave radiometers are calibrated and fielded annually by the ARM Program. To provide calibration traceable to the World Radiometric Reference maintained by the Physikalisch-Meteorologisches Observatorium Davos/World Radiation Center (PMOD/WRC) in Switzerland, a Radiometer Calibration Facility (RCF) was established in 1997 at the ACRF Southern Great Plains Central Facility under the guidance of the National Renewable Energy Laboratory (NREL). The RCF, patterned after an NREL facility that helped serve this calibration function before 1997, is comprised of a 45-ft trailer and two elevated decks (Fig. **2**); it houses calibration electronics, a data acquisition system, a repair laboratory for radiometer technicians, storage for reference cavity radiometers and spare radiometers, and a broadband longwave radiometer calibration blackbody [28]. One of the elevated decks includes mounting spaces equipped with hail shields for up to 50 radiometers. Another

elevated deck surrounds four Brutsag solar trackers, which are mounted on concrete piers independent of the deck, and can accommodate eight normal incidence pyrheliometers each.

The RCF is designed to calibrate radiometers in outdoor conditions similar to those the instrument can experience during field operations. Calibration is achieved annually during a Broadband Outdoor Radiometer Calibration (BOR-CAL) event, an activity initiated in September 1997. During a BORCAL, electrically self-calibrating, absolute cavity radiometers are used to calibrate pyrheliometers and pyranometers. Procedurally, spares are calibrated and swapped with half of the radiometers in the field; then, the radiometers brought back from the field are calibrated and swapped with the remaining half in the field, which then become spares awaiting calibration the following year. Calibration results are processed and reviewed for validity by the instrument mentor and his associates at NREL.

Fig. (2). Radiometers on a Radiometer Calibration Facility deck located near Lamont, Oklahoma.

Additionally, the RCF is equipped to calibrate broadband longwave radiometers; this calibration is based on exposures to temperature-controlled blackbodies and on outdoor comparisons with standard pyrgeometers, and is consistent with the World Meteorological Organization's Baseline Surface Radiation Network (BSRN) calibration protocol. A pyrgeo-

meter blackbody calibration system was installed at the RCF in April 2002.

4. INSTRUMENT AND SITE MAINTENANCE

ACRF field technicians, under the guidance of site operators who coordinate site activities and instrument mentors and vendors who establish procedures, perform preventative and corrective instrument and site maintenance and collect and store the information describing the results of their activities. The maintenance process consists of a cycle of structured activities that result in a continuous, repeatable effort, with the primary objective of ensuring instrument and site performance and reliability, all the while achieving cost efficiencies. A reliable maintenance capability requires efficient, timely procurement of parts and services to repair failed components. An electronics repair laboratory was established in 1998 at the Southern Great Plains Central Facility to serve all ACRF sites; its on-site repair capability has resulted in reduced instrument downtime and costs. Maintenance activities are described below for each climate research facility since they vary slightly due to site geography, remoteness, and climate.

4.1. Southern Great Plains Facility

Preventative maintenance is performed on a bi-weekly basis at Southern Great Plains field sites, including 24 extended facilities, four boundary facilities, and three intermediate facilities distributed across Oklahoma and Kansas. Each week, two 2-person field technician teams conduct multi-site visits. One week, the two teams service sites in the northern half of the collection domain and the following week they service the southern half, with the schedule repeated continuously. Visited sites are divided to make the most efficient use of time and resources. At the Central Facility, where the operations center is located, most instruments receive daily preventative maintenance on week days. Corrective maintenance is performed as requested at each site.

Upon arrival at a site, the technician team performs checks on all site instruments and communication equipment. A detailed, instrument-specific checklist for each of the instruments is annotated through use of a field-hardened laptop computer. These laptops are connected directly to some data loggers so that real-time sensor voltages and measurement values can be recorded. If the data logger values fall outside an expected range, the applicable data base field is marked as an observed problem and troubleshooting begins. Detail is then provided on the suspected root cause of the failure, along with the name of the specific component that failed. Previously-identified problems are addressed *via* a work order that specifies an instrument mentor corrective maintenance procedure to be performed. Site activities also include maintenance and documentation of vegetation conditions, plus a safety inspection. Maintenance teams may be dispatched at irregular times for emergency corrective repairs, especially during field campaigns when certain instrumentation has been deemed critical for the campaign's success. A web-based database system is used to capture all metadata generated during site visits.

4.2. Tropical Western Pacific Facility and ARM Program Mobile Facility

Two of the three Tropical Western Pacific data collection sites, Manus Island and the Republic of Nauru, are geographically remote, which significantly complicates on-site maintenance activities. A multi-tiered approach has been developed that includes routine on-site maintenance performed by trained local staff under the guidance of a team of ACRF technicians based at Los Alamos National Laboratory in New Mexico and as of 2002 at a Bureau of Meteorology operations center in Darwin, Australia. The ACRF technicians periodically visit the sites to perform major actions. The on-site staff performs an assortment of system checks on a periodic basis, including daily inspection of instruments, and communicates as necessary with technical staff. The collaborative arrangement with the Bureau of Meteorology included the installation of a third Tropical Western Pacific data collection site in Darwin, adjacent to a Bureau observation facility. Because it is significantly easier to travel to Manus and Nauru from Darwin than from New Mexico, this arrangement has facilitated more frequent technical visits to the islands and has led to a significant decrease in the time between major repairs; this has led to a resultant improvement in data availability and quality.

In 2004, a mobile platform was designed and integrated into the ACRF measurement suite to address under-sampled yet climatically-important regions of the world. The ARM Mobile Facility, with a suite of instruments similar to those at Manus and Nauru, was deployed first in March 2005 for six months at Point Reyes, California. It subsequently was deployed at Niamey, Niger, in 2006, at Heselbach in Germany in 2007, and at Shouxian and Taihu, China, in 2008. The Darwin operations center works together with the support function of Los Alamos to provide technical guidance for mobile facility deployments. Due to the temporary, focused nature of these deployments and the effort required to support them, "24/7" technical support is provided to minimize instrument downtime. This support includes a full-time, on-site technician who is wholly responsible for the operation of the site.

4.3. North Slope of Alaska Facility

North Slope of Alaska facilities also are remote, and Arctic weather conditions and wildlife often limit or make challenging outdoor activities. Identification of problems and corrective actions, and the scheduling of preventative visits occur through collaboration among local on-site observers, the North Slope site scientist team, instrument mentors, data quality analysts, and a rapid response team at the University of Alaska-Fairbanks. North Slope facilities include a primary site in Barrow maintained by two full-time staff, and a smaller secondary site in Atqasuk staffed by one part-time operator. At Barrow, operators perform weekday preventative maintenance on all permanent instruments as well as daily-to-weekly maintenance as specified on visiting instruments. At Atqasuk, preventative maintenance is performed three times per week. Corrective maintenance is performed by the local operator or instrument mentor; some can be ac-

complished remotely by the instrument mentor *via* access to instrument data loggers.

4.4. Continuous Quality Improvement Program

A Continuous Quality Improvement Program was implemented at the Southern Great Plains and North Slope sites as a way to evaluate how a site is performing. It consists of periodic on-site audits by the site scientist, the site operations safety officer, the site instrumentation and facilities manager, and the ACRF environmental safety and health coordinator. This diverse team examines site grounds and instruments, periphery equipment, maintenance procedures, and technician proficiency. Audit data are analyzed and provided to site operators and field technicians to foster work process improvements.

5. DATA COLLECTION AND PROCESSING INFRASTRUCTURE

The focus of the data collection and processing infrastructure is to efficiently transport data generated by remotely-fielded instruments to a central distribution point [29]. The remoteness of ACRF sites and the diversity of the

instruments deployed add to the complexity of the required solution. Communications access to sites often is limited, which significantly impacts options for data flow architecture and management. Through several iterations and significant effort to establish Internet connectivity to each site, an efficient data flow process has been implemented that tracks data integrity and timeliness from the instrument system to the central distribution point and ultimately to the Data Archive (Fig. **3**). Network and computing infrastructure now centrally process data from all sites on an hourly basis and make data available to the user community on a daily basis. This is accomplished through the use of satellite networking, specialized data movement processes, and a tight configuration management process. Key locations along the data flow route include the Data Management Facility at Pacific Northwest National Laboratory, where all raw data are received and processed, and the Data Archive at Oak Ridge National Laboratory, where processed data are made available to the public. The data flow architecture is logically implemented by routing Internet traffic from the collection sites *via* a Virtual Private Network Server Network located at Argonne National Laboratory.
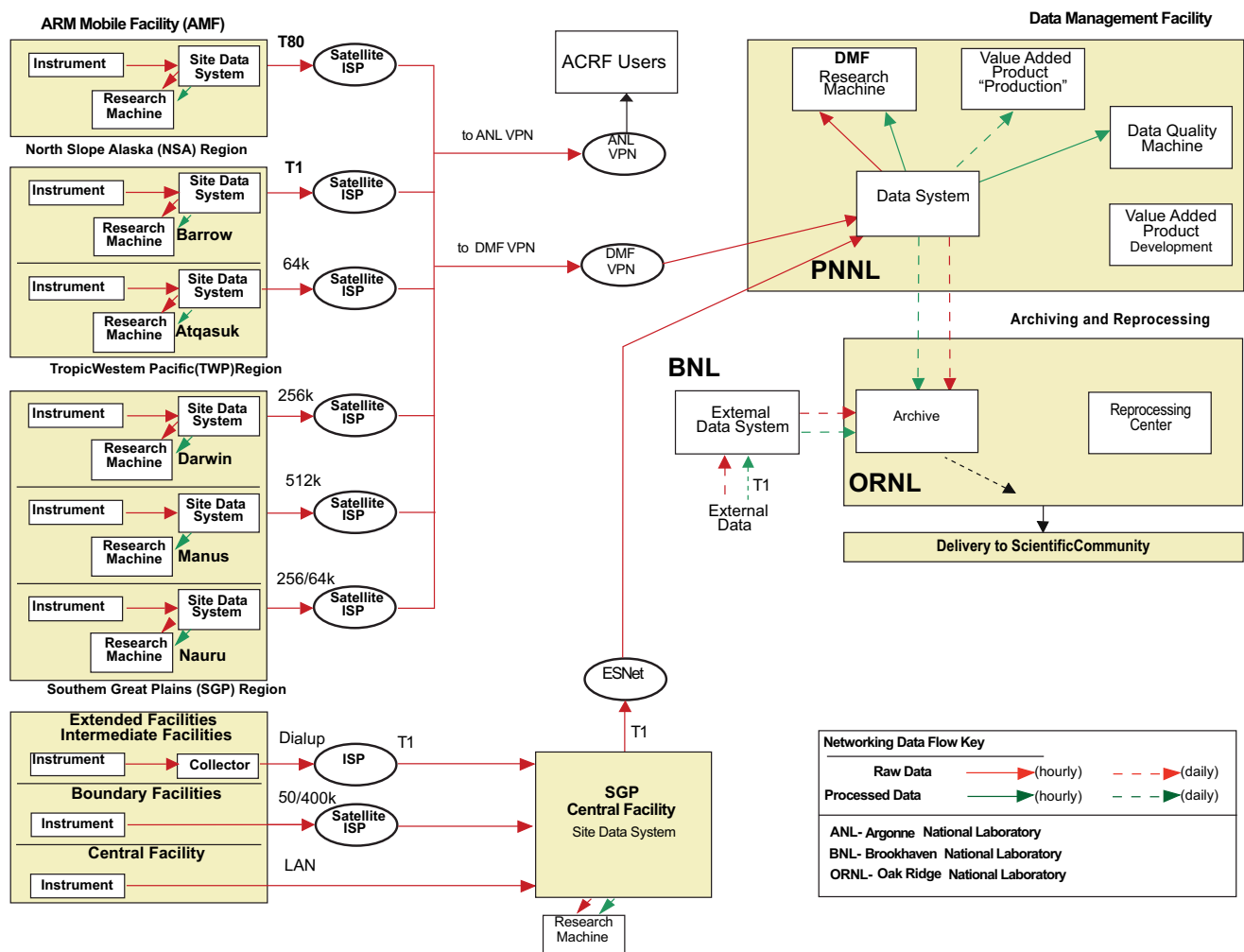

Fig. (3). ARM Program Climate Research Facility data flow architecture. PNNL is Pacific Northwest National Laboratory, BNL is Brookhaven National Laboratory, ORNL is Oak Ridge National Laboratory, and DMF is Data Management Facility.

5.1. Internet Connectivity

Internet connectivity includes a T1 link from the Southern Great Plains Central Facility to an Energy Sciences Network (ESNet) peering point at Oak Ridge. Other Southern Great Plains collection sites use a continuous, low-speed (20−50 Kbps) satellite link or a land-line modem dial-up to a local Internet Service Provider (ISP). At Manus and Nauru in the Tropical Western Pacific, the connectivity is accomplished with satellite ground stations that support 256-Kbps outbound and 64-Kbps inbound channels. The Darwin facility uses a 512-Kbps frame relay link to an Australian service provider. At Barrow on the North Slope of Alaska, the site shares a satellite-based T1 link partially funded by the National Science Foundation, while the Atqasuk facility uses a symmetrical 64-Kbps satellite link through a commercial ISP.

The variety in types of infrastructure is a result of identifying the most appropriate available technology that will support the data transfer requirements of each remote facility in the most cost-effective manner, and is dynamic. Access controls are in place to ensure that the remote sites are operated in a continuous, highly-reliable manner. Data flow analysts at the Data Management Facility are able to monitor the individual site data systems through a graphical user interface (Data System View) that provides a real-time glimpse of site collection and ingest status (Fig. **4**). It provides access to system resources and views of data throughput that can help identify problems early in the quality assurance process.

5.2. Measurement Time Accuracy

A critical characteristic of a measurement is the accurate synchronization of its time stamp with a universally-recognized time reference. The ACRF data collection and processing infrastructure uses the Network Time Protocol (NTP) to maintain accurate time synchronization. Each measurement site and the Data Management Facility utilize a commercially-available Global Positioning System (GPS) network time reference. Instrumentation that is not network connected but uses an RS-232 or equivalent interface has its internal clock compared to that of the GPS reference by a Linux collector system, which uploads the data from the device. An instrument clock time will be reset whenever the time difference exceeds twice the instrument clock resolution.
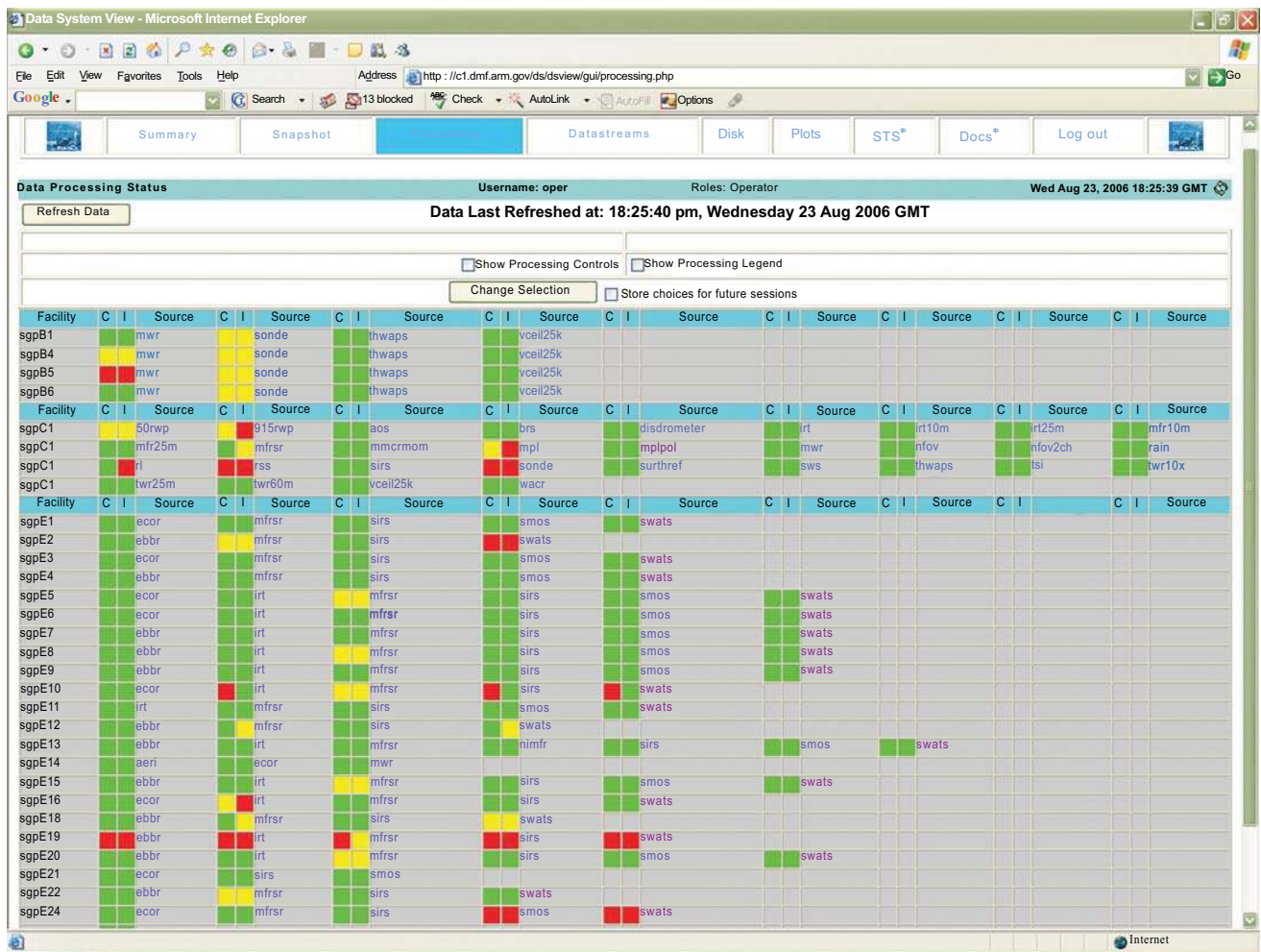

Fig. (4). Data System View user interface that allows data flow analysts and site operators to view and monitor current collection ("C") and ingest ("I") status and to enable or disable either. Sites are listed under "facility" and instruments are listed under "source".

5.3. Site Transfer Processes

Moving data in a reliable manner is one of the essential functions of the data collection and processing infrastructure. The greatest risk of data loss or corruption occurs in the transfer of files across wide area networks. To mitigate this risk, a Site Transfer Suite (STS) was developed. This software uses File Transfer Protocol (FTP) to send data between the sites and the Data Management Facility. The STS uses MD5 checksums (a type of electronic fingerprint) to validate successful data transfer. The checksums are transmitted twice, with each validated on the receiving host, ensuring the integrity of the data. Files that fail checks are automatically resent.

While data integrity is the first concern of the STS, the limited bandwidth available to some sites presents additional challenges. It is operationally important to know the state of the remote sites as well as that of each instrument. If a backlog of one instrument is allowed to dominate file transfers, it will prevent efficient management of the sites and of data flow. The STS provides configuration options that include data prioritization and use of multiple threads for different data sets. This ensures that essential operational information is sent first and larger data sets are sent as a lower priority, so that overall delivery is achieved in a timely manner. In general, all hourly data are shipped from each site to the Data Management Facility within 20 minutes of last collection.

6. DATA STREAM INSPECTION AND ASSESSMENT

Nearly 5,000 data fields from 315 instruments are generated on a daily basis. Given this data volume, data inspection and assessment activities must be efficient and as automated as possible. To this end a Data Quality Office was established in July 2000 at the University of Oklahoma to help coordinate these activities across the various ACRF sites.

The objective of data inspection and assessment is to identify data anomalies and report them to site operators and instrument mentors as soon as possible so that corrective maintenance actions can be scheduled and performed. This is a team effort involving several groups. While data quality analysts located in the Data Quality Office perform the routine inspection and assessment functions, instrument mentors, site scientists, and site operators contribute key functions. Instrument mentors, as the technical authorities for the instruments, provide in-depth instrument-specific guidance and perspectives on data quality, and are responsible for resolving problems and identifying long-term trends in the data. Site scientists, as the authorities on their locale and its scientific mission, provide a broad perspective on data quality spanning the full range of site instrumentation and oversee their site's problem resolution process. They also perform targeted research on topics related to site data quality and interact with the science community to plan and conduct field campaigns at their sites, which in the past have identified previously-unknown data quality issues. Site operators implement the problem-resolution process by orchestrating and conducting the corrective maintenance actions required.

To facilitate data inspection and assessment efficiently, the Data Quality Office has, with the technical guidance of instrument mentors and site scientists, developed automated tools and procedures packaged into the Data Quality Health and Status (DQ HandS) system (http://dq.arm.gov/; see also [30]). It facilitates inspection of ACRF data streams and initiates the problem resolution process. ACRF network configuration allows the Data Quality Office to share a file server with the Data Management Facility, which facilitates data quality algorithm processing. A DQ HandS prototype was created in the late 1990s by Southern Great Plains site scientists as a way to monitor solar trackers and was later expanded to monitor a soil water and temperature system [31]. It then was formalized into a program-wide, web-based data quality tool. Every hour, the latest available ingested data at the Data Management Facility is processed by DQ HandS to create a summary of bit-packed integer quality control fields (flagging) within each file. When quality control fields are not available within a data stream, data quality analysts work with instrument mentors to identify flagging values for range and change to be processed and outputted directly by DQ HandS.

Data quality analysts use the DQ HandS user interface to select the site, data stream, and date range of interest for analysis. A color table then is displayed showing flagging summaries by day that quickly identify potential problem areas; it uses a red/yellow/green color system that bins the data by the percentage passing the range and change tests. From these daily results, a more detailed hourly table of flagging results can be obtained, and a mouse-over capability provides a pop-up of flagging details for any particular hour and measurement, including the percentage of tests violated (Fig. **5**). All color tables are updated hourly as data arrive to the Data Management Facility.

Data quality analysts also visually inspect all data. Diagnostic plots, including cross-instrument comparisons, display data for one day and are similarly updated hourly. Inspection of these plots, which show primary and other diagnostic variables produced by an instrument, help identify data abnormalities not always detected by automated tests. These plots have color-coded backgrounds to indicate local sunlight conditions, helping analysts distinguish between night and day.

Two other plotting capabilities aid the analyst. The first provides viewing of a succession of daily diagnostic plots in thumbnail form, which can illustrate trends in data (http://plot.dmf.arm.gov/plotbrowser/; Fig. **6**). Analysts may select a site, an instrument, and a date range, and can view thumbnails for up to 30 days at a time. The thumbnail format facilitates comparison of different instruments that measure like quantities. A user may filter thumbnail results by facility and plot type, and can step forward or backward in time while retaining current filter options.

The second capability provides the analyst with an interactive, web-based plotting tool, NCVweb (http://plot.dmf.arm.gov/ncvweb/ncvweb.cgi; Fig. **7**). It works by querying the metadata within each file of interest, meaning that the data quality analyst does not need to be
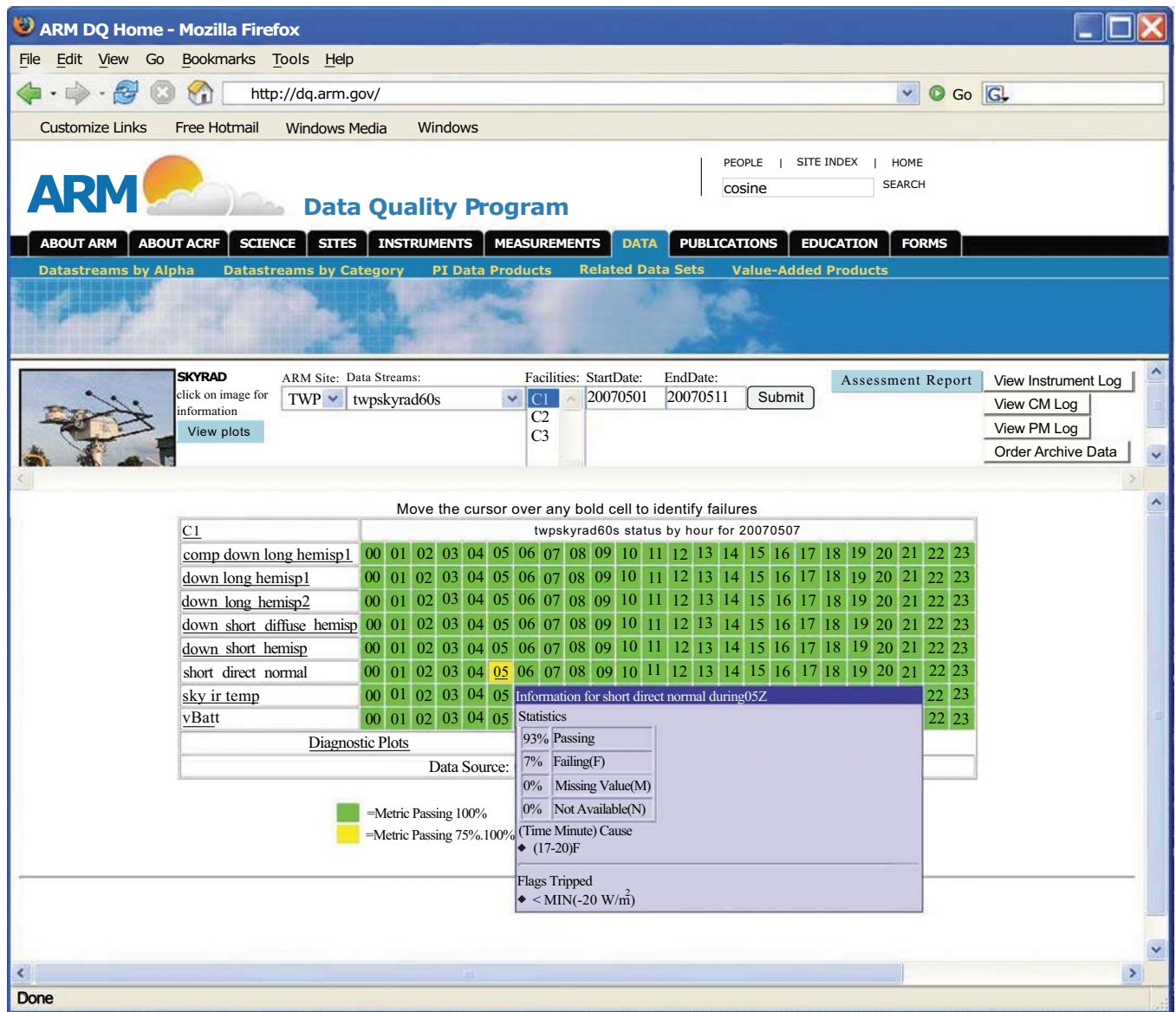
Fig. (5). Hourly color table of automated quality control check results for one day (7 May 2007) at the Tropical Western Pacific Manus Island site. The blue pop-up window of flagging statistics is obtained by mousing over the yellow shaded box for 0500 UTC for the shortwave direct normal incidence measurement; here, 7% of the observations failed a minimum test.

conversant in the NetCDF file format to manipulate the data. Key features include zooming on data periods of less than one day and plotting multiple data files (days) at one time. Particular data fields of interest can be specified from pull down menus. Plots may consist of one or more independently-plotted fields, multi-dimensional color-coded images such as radar spectra, or slices through a multidimensional array. For closer inspection, data values can be displayed in tabular form or downloaded in ASCII comma-delimited format for easy importation into spreadsheet applications. Analysts can view file headers to obtain direct access to metadata or can obtain a summary of data field descriptions and basic field statistics.

Data analysts also need supporting information in order to determine if what they are seeing is worth reporting. Such information is made linkable within DQ HandS to assist the

analysts. It includes information from maintenance field report databases and data availability statistics from the Data Management Facility, plus it provides links to basic information about instrument operational characteristics and calibration.

7. PROBLEM REPORTING, REVIEW AND RESOLUTION

Once data have been inspected and assessed, a variety of reporting mechanisms allow the data quality analyst to inform instrument mentors, site operators, and site scientists of their findings. Data quality reporting mechanisms are based on searchable and accessible databases (administered at Brookhaven National Laboratory) that allow the various pieces of information produced during the quality assurance
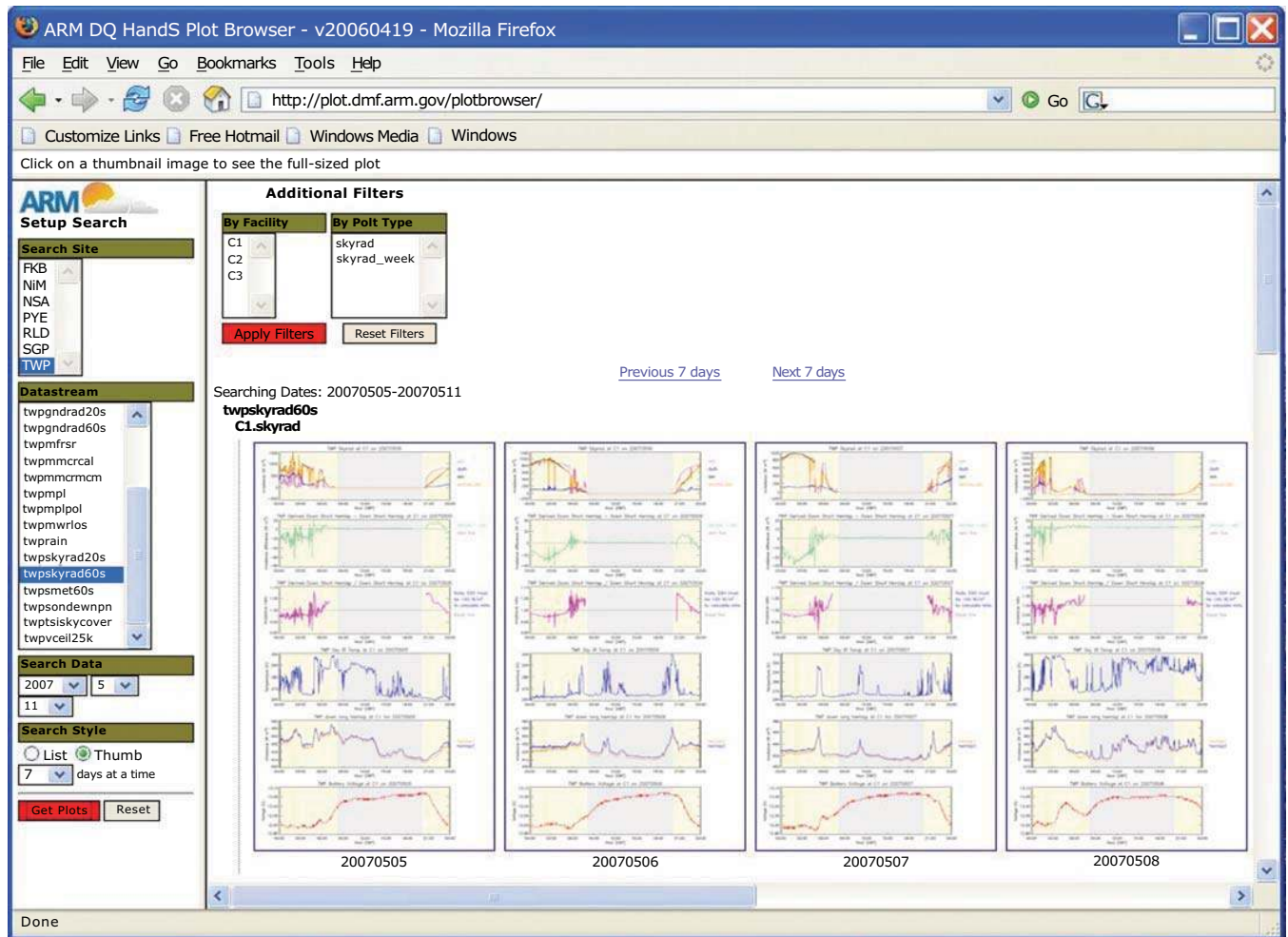
Fig. (6). Plot browser screen shot of downwelling radiation plots for 5-8 May 2007 corresponding to the example in Fig. (**5**).

process to be neatly conveyed to problem solvers in a timely manner.

The problem reporting system is divided into four linked subsystems: (1) weekly assessments of data inspection results - documented in a Data Quality Assessment report system; (2) routine problems that can be addressed by site operators under the guidance of instrument mentors and site scientists - documented in a Data Quality Problem Report system; (3) significant problems that require engineering effort or that cannot be solved in a timely manner through the efforts expended in (2) - documented in a Problem Identification Form/Corrective Action Report system; and (4) the resulting impact on data quality of any problem type - documented for the data user by the instrument mentor in a Data Quality Report system. The complete history of problems, corrective actions, and reports on data quality is searchable on many criteria. The linked databases allow for the tracking of problem trends and help identify problematic instrument systems that might require design modifications to make them more reliable. The reporting process, using the various forms, is described as follows.

Once a data inspection and assessment has been performed, the data quality analyst creates a Data Quality As-

sessment using the DQ HandS interface. This report is e-mailed automatically to the appropriate instrument mentor, site scientist, and site operator. Such reports are issued weekly for all data streams and are for informational purposes.

If a data quality anomaly is discovered during the inspection and assessment process, the Data Quality Assessment report interface pre-populates key fields in a Data Quality Problem Report. This report alerts the appropriate instrument mentor, site scientist, and site operator of a potential instrument performance issue. A key feature of this reporting mechanism is its ability to capture the ensuing conversation that documents the progress and status of the diagnostic and corrective actions proposed and implemented. This report remains open until a solution is implemented and will not be closed until the corrective action has been deemed successful through subsequent successful data quality analysis. The site scientist oversees the progress of problem resolution at his/her site and has the authority to change problem status and make work assignments as necessary.

If a problem cannot be resolved through the Data Quality Problem Report process within 30-45 days of issuance, it is elevated to Problem Identification Form status, which brings
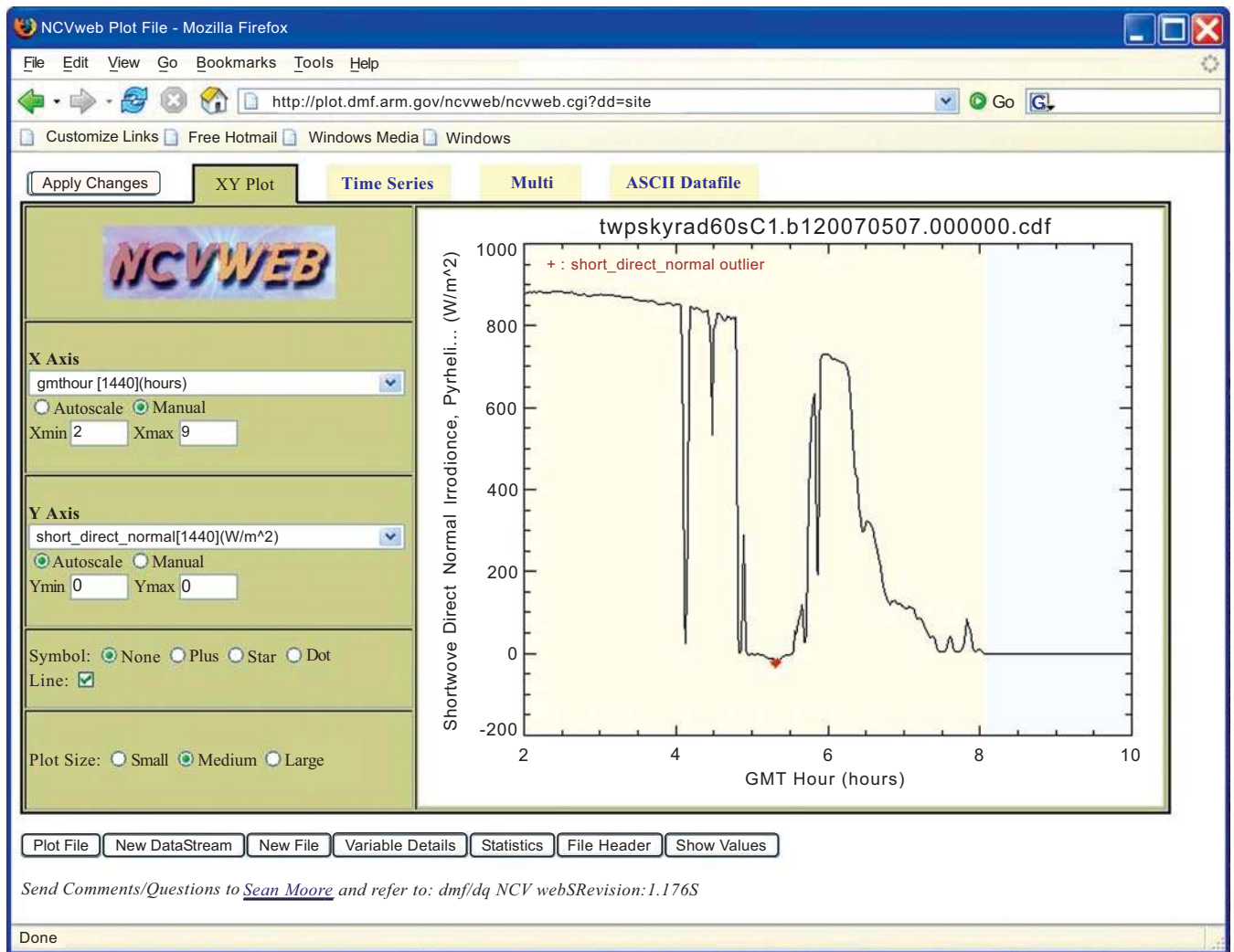
Fig. (7). NCVweb zoom on the hours 0200-1000 UTC of the shortwave direct normal measurement on 7 May 2007 corresponding to the example in Figs. (**5**,**6**), showing values (red asterisk) denoted in Fig. (**5**) that violated a minimum test.

it to the attention of key ACRF infrastructure personnel that make up a Problem Review Board. If a problem is of such gravity that it requires the immediate attention of the Problem Review Board, it is entered into the Problem Identification Form system immediately upon discovery. This form may be submitted by anyone involved in the production or use of ACRF data, including ARM Science Team members and anyone outside of the ARM Program that discovers a data problem during their analysis. The Problem Review Board meets once a week *via* teleconference to review new problems and track progress on existing problems. It assigns a problem to the most appropriate person that can take responsibility for its resolution. It also assigns a resolution priority to each problem and specifies an e-mail distribution of people that need to know about it. The assignee is asked to determine an estimated date of completion. The assignee supervises and monitors problem resolution and submits attachments that serve as progress reports toward correction of the problem. The assignee also writes a Corrective Action Report when the problem has been resolved, which closes out the problem resolution process with a description of what was done to correct the problem.

Both a closed Data Quality Problem Report and a filed Corrective Action Report trigger the issuance of a Data Quality Report to the user community, ending the reporting chain. Any issue having a bearing on the quality of the data is ultimately summarized by the instrument mentor in terms of severity, affected measurements, and time periods covered. If relevant, suggestions are provided to the data user on how to correct or replace affected data. These reports are included with data files at the Data Archive upon data delivery to a customer and are retroactively sent to those that previously ordered the affected data. They are worded such that the nature of the problem is fully described without use of excessive jargon. The theory behind these reports is that they will provide end users with the information needed to make informed judgments on whether and how to use the data.

8. DATA ARCHIVAL, DISPLAY AND DISTRIBUTION

Once the data have been collected, processed, and checked for quality, they should be made available for distribution in a way that will encourage their use. The ARM Program Data Archive was established to store and distribute the data collected at ACRF sites. Its primary functions are to

store and accurately represent the existence of data files, provide access to all requested files, and to present specific and complete quality information for all files. In-house quality assurance of the data archiving operation itself is performed to guarantee the success of these functions.

8.1. Data Access and Distribution

ACRF data are made freely available for use by the science community. Anyone interested in ordering data may explore the Data Archive's holdings by pointing their web browser to http://www.archive.arm.gov/; searches may also initiate from the ARM Program home page (http://www.arm.gov/). There are a number of options with which to initiate and execute a search. A prospective data user often begins by specifying a site and a date range, followed by choices of instrument or measurement. As the search narrows, graphical displays of data can be requested; it is at such time that summaries of quality assurance information become viewable. When the data of interest have been defined, the files containing them can be ordered. Automated processes retrieve and stage the files and their associated data quality information for retrieval by FTP. Help information also is made available.

8.2. Display of Data and Related Quality Information

Several types of data quality information are offered or displayed during a user's process of data selection. Quick-look graphs, including thumbnails of scientifically-relevant measurements, let the prospective data user judge visually the nature and completeness of the data before actually ordering them. Thumbnails are displayed by a user-customizable interface capable of concurrently displaying multiple measurements from multiple instruments (Fig. **8**). Color tables of in-file data flagging results are displayed for each scientifically-relevant measurement (Fig. **9**). An assigned color is a single classification of the preponderance of the file's quality control flag states for the measurement's samples during a day (green denotes good quality; yellow denotes suspect quality ; red denotes poor quality; black denotes missing data; gray denotes undetermined quality; white denotes quality review is pending). Color-coding symbols are used to indicate whether Data Quality Reports exist for this measurement during the particular day being considered; these reports also can be listed by title along with a link to the report's text. This varied quality information palette is provided to help the user confirm his or her selection or modify it to something more appropriate.

8.3. Data Archiving

The efficacy of access, distribution, and display depends on the efficacy of many underlying Data Archive processing activities. These functions are accomplished by means of structured data stream and file naming conventions, the design of the Archive's metadata database, and intricate logic that relies on consistent metadata content for each data stream in the database. These naming conventions in turn have implications for the structure of the Data Quality Reports, and have resulted in in-house quality assurance procedures that are executed during the process of data file ingest into the Archive, as explained briefly below.

Structured data stream naming conventions are fundamental to enabling the Archive to carry out its function. A data stream is a collection of successive daily files of a particular type. The leading fields in a NetCDF filename denote a site and a particular facility within the site, instrument name and data integration period (for some files), data level (e.g., raw or processed), date of the first measurements in the file, time of these first measurements, and the file's format. The key to this convention is that the filename contains all of the information needed to identify the location, file type, and the initial date/time of its contents. The first two of these fields define the data stream to which the file belongs. The structured filenames then facilitate the organization and function of a metadata database. Each filename has entries for its start date/time, end date/time, number of samples, file size, MD5 checksum, a version number, and the date the file was received by the Archive. Many additional integrated metadata database reference tables allow the filenames, based on the data streams to which they belong, to be grouped in various ways (e.g., space, time, instrument class, measurements) according to the needs of the data user. For example, twelve categories of ACRF instruments have been defined. Each data stream represented in the database is associated with one or more of these instrument categories. When a data user selects an instrument category while browsing, a list of instrument links is shown that in turn display a list of data streams available from each instrument.

The information that populates the integrated metadata reference tables needs to be complete and consistent; this allows the data user to find the same data stream from different web page starting points. A process was devised to collect this needed metadata starting right at the point of data stream design; i.e., when an instrument is about to be fielded. Related tools enable updating of this information as required and allow the process to change and evolve as needed without introducing downstream synchronization issues. A special Data Quality Report metadata database was developed to allow for correct report/data file associations when displaying and disseminating data.

8.4. Internal Quality Assurance for File Processing

To properly accomplish all of the tasks outlined above, the Data Archive implements in-house quality assurance procedures to make sure that file processing is conducted seamlessly. Some procedures are directed at ensuring that the Archive does not lose or corrupt any of the thousands of files it receives daily from the Data Management Facility; others focus on those elements of file names and their contents that are stored in the Archive database, enabling the Archive to identify and deliver the correct subset of files as requested. These checks enable the Archive to store all files, protect them against corruption, display holdings in logical and useful ways for ordering, and provide all files (and only those files) needed to fulfill a data request. These procedures, comprising a ten-step process, are described in [1].

9. DATA STREAM REPROCESSING

At times, it is necessary to reprocess data when previously-unknown data quality issues come to light through the

results of a new data quality analysis or someone's scientific research. The ACRF Reprocessing Team is tasked with reprocessing data to fix known problems when clear corrections are available. Examples of correctable problems include calibration errors or offsets, metadata coding errors, and updates to remote sensing retrieval techniques. Reprocessing helps produce a consistent data format across sites and time to improve the usability of data for data users and the input to value-added data processing algorithms. A reprocessing task can be as targeted as correcting a few days of data in a single data stream or as encompassing as an end-to-end reprocessing of an entire data class.

Reprocessing tasks often are identified during a problem resolution process. When a correctable data quality problem is identified, a reprocessing task is submitted to the reprocessing database and is assigned an appropriate priority by the Problem Review Board. Since reprocessing can be an involved and time-consuming process, a Data Quality Report is distributed to data users to alert them of the problem until the reprocessed data are created and become available.

Before a reprocessing task is undertaken, any ancillary problem reports associated with the data stream to be corrected are reviewed to identify other problems that could be corrected during reprocessing. The existing Data Quality Reports written on the record of data in question also are pre-reviewed for opportunities to merge documentation of like-quality problems into a single consolidated report. Additionally, data stream structural changes through time are identified so that these can be addressed, if appropriate, to produce data of a consistent format. This allows for the reprocessing of the associated metadata as the data they describe are reprocessed.

After the reprocessing has been performed and before the data are released to the Archive, the reprocessed data set must be thoroughly reviewed to verify that the reprocessing was properly accomplished. A series of tests are performed, and at any point in the verification process the failure of a test will result in the data being returned to the reprocessing center for additional processing or correction. These include a completeness check (to compare the original data set to the reprocessed data set for gaps, file splitting, and discrepancies in the number of records written, all to make sure that no new problems have been introduced by the reprocessing); a file header comparison check (to identify metadata changes throughout the reprocessing period to guard against unintended differences between, for example, calibration coefficients or serial numbers); spot checks using a plotting tool (to confirm that the intended corrections have been applied and that no unintended changes have occurred to variables that should not have been modified by the reprocessing, including ensuring continuity with the data immediately before and after the reprocessing period); and finally a post-review of all relevant problem reports, Data Quality Reports, and associated metadata (to ensure that valid advisory information is provided to data users, including the sanitization and/or merging of Data Quality Reports to accurately reflect the reprocessed data set as well as to succinctly communicate to the data user all known data quality concerns). Only after

successfully passing these tests are the reprocessed data cleared for archival and release.

10. ENGINEERING AND OPERATIONS MANAGEMENT

In order to link the various components of the quality assurance program and promote optimal systems performance, the ACRF infrastructure has established formal processes and procedures to identify, develop, perform, and manage engineering and operations changes; it also allocates the resources needed to perform them. These are described below.

Engineering activities include the development, maintenance, and modification of instruments, sites, data systems, and communications systems. An engineering change management system was developed to track such activities, and serves as the starting point for adding or modifying an instrument capability, data product, or system functionality. Required engineering tasks are initiated and managed through specific design processes. The process flow, culminating in a request for operational change, is illustrated in Fig. (**10**).

To institute a fundamental change (as perhaps identified through data quality analysis) or add a new capability, the engineering process begins with an Engineering Change Request (ECR). An ECR describes the reason for a change and indicates any known costs and/or impacts to current operations or systems. It also contains detail on the requirements definition, analysis, design, documentation, testing, training, and delivery. An Engineering Review Board meets weekly to review requests and to approve or reject them, and assigns priority to approved requests. When priority is assigned, an ECR is considered in the overall context of the ACRF infrastructure workload so that the programmatic impact of performing ECR-specified work is understood and communicated. Once approved, an Engineering Change Order (ECO) process begins. It documents estimated project duration, task status, project impacts and resources, requirements and design reviews, and at the end, a readiness review. To close this process, all requirements as defined must be met and approved. A task tracking tool helps manage all engineering processes. It is used in particular to perform resource loading, track and communicate status, and schedule and set priorities. Tracking ranges from daily (for emergency priority projects) to twice yearly (for routine priority projects). The Engineering Review Board reviews a summary of all engineering tasks to ensure the right balance of tasks is undertaken and may reassign resources as needed to support programmatic priorities.

Once an engineering solution has been developed and successfully tested, a Baseline Change Request (BCR) process is initiated to formally request, implement, and document the requisite change in baseline operations. This process helps ensure that all components of the ACRF quality assurance infrastructure are consulted prior to implementing a change, as even minor changes can have significant repercussions. Activities are prioritized to understand what is required to make a change and a signal point of contact is des-
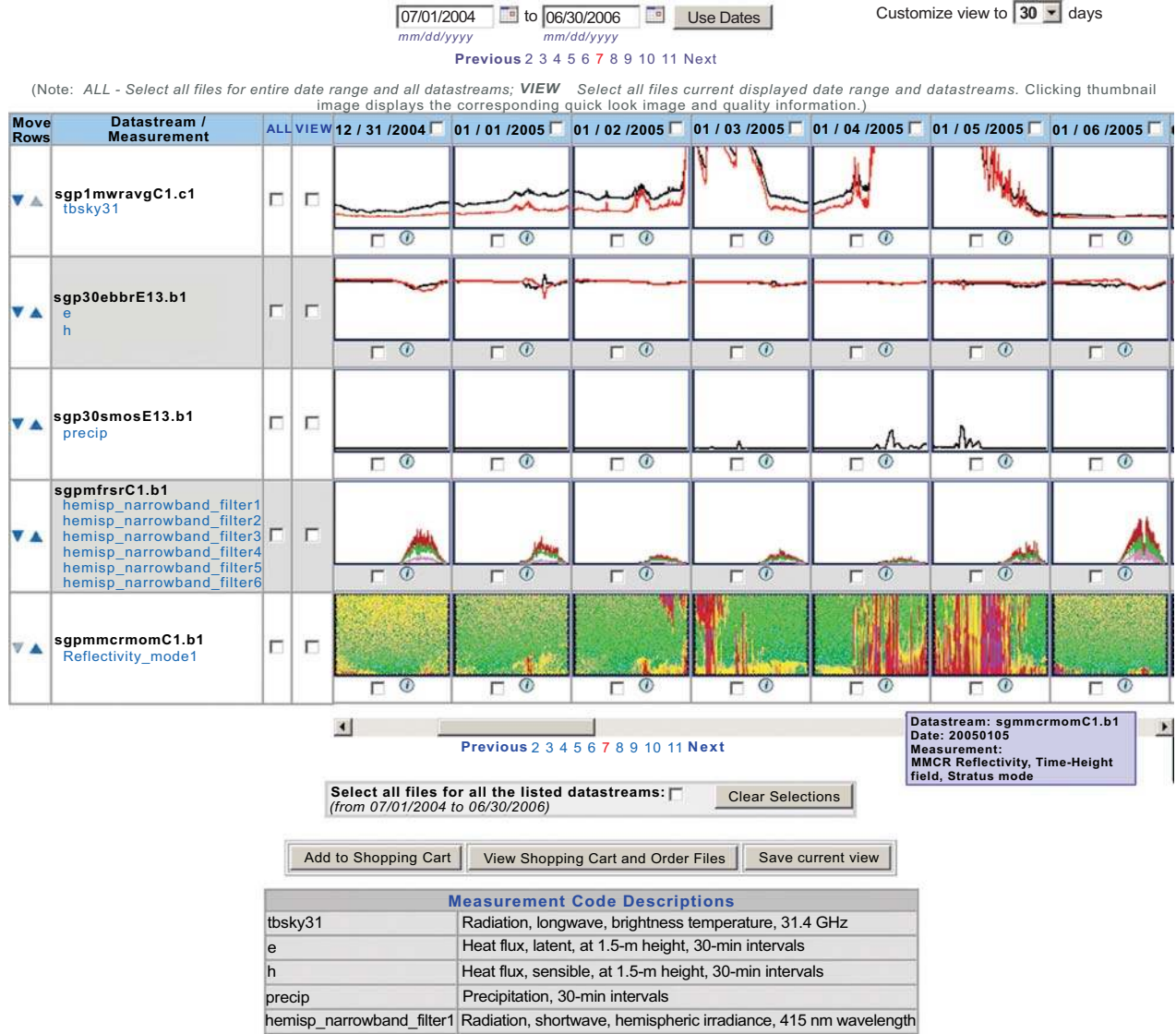
Fig. (8). Thumbnail plots generated in the Data Archive Thumbnail Browser. A mouse-over pop-up window at lower right provides detail for one of the thumbnails shown. Clicking on a thumbnail plot will display a full-size quicklook plot and all available related data quality information.

ignated that ultimately is responsible for seeing the proposed change to completion. A searchable database captures reviewer and coordination comments and updates. Once the implementation activity has been completed, the change is evaluated for several weeks to assess and document any unanticipated impacts.

11. ROLE OF VALUE-ADDED DATA PROCESSING IN DATA QUALITY ASSURANCE

Some of the scientific needs of the ARM Program are met through the creation of value-added data products (VAPs; http://www.arm.gov/data/vaps_all.php). Despite the extensive instrumentation deployed at the ACRF sites, some quantities of interest are either impractical or impossible to measure directly or routinely - VAPs provide high-quality

data to fill this void. This is accomplished through sophisticated interpretations of measurements (e.g., indications of cloud fraction from measurements of solar radiation; estimates of cloud microphysics from radar and lidar data), while at the same time evaluating measurements through the constraints physical understanding (i.e., do the retrieved quantities make sense in the context of the surrounding physical situation?). VAPs ultimately embody the scientific judgment of the ARM Program's scientific working groups with respect to what is needed data-wise by the climate modeling community and as such represent the state of the science with respect to characterization of clouds and atmospheric radiation by measurements. Importantly, the processing of VAPs has shed much light on the quality of the data streams used to create them, including through their routine

Measurements:
1) Precipitation, 30-min intervals
2) Wind speed, at 10-m height, 30-min intervals
3) Wind direction, at 10-m height, 30-min intervals
4) Humidity, relative, at 2-m height, 30-min intervals
5) Temperature, air, at 2-m height, 30-min intervals
6) Pressure, vapor, at 2-m height, 30-min intervals
7) Pressure, atmospheric, at 2-m height, 30-min intervals
8) Wind speed, vector-averaged, at 10-m height, 30-min intervals
9) Wind speed, 30-min intervals, standard deviation
10) Wind direction, 30-min intervals, standard deviation
11) Humidity, relative, 30-min intervals, standard deviation
12) Temperture, air, 30-min intervals, standard deviation

Note: Colors inside the box represent auto quality check (Auto QC) colors and the symbols inside the box represent Data Quality Report (DQR) colors

Legend (color:status):

| ■: Missing | ■: Undetermined | □: Review Pending | ■: Good | ■: Suspect | ■: Incorrect |

Symbol

| G: Green DQR | Y: Yellow DQR | R: Red DQR |

Calendar Date Range: 3-1-2006 TO 4-30-2006

Help

DQRID : D060321.2			
Start Date	**Start Time**	**End Date**	**End Time**
03/02/2006	1806	03/17/2006	1706
Subject:	SGP / SMOS / E13 – Reprocess: Baromet		
DataStreams:	sgp 1 smosE13.bl,sgp30smosE13.bl,sg		
Description:	The Programs was modified and an i was reported in hPa instead of kP		
Measurements:	sgp1440smosE13.bl:		

Fig. (9). Color table display from the Data Archive Data Browser. The color of a cell displays a summary of data quality status and data existence for a measurement on a particular day. "Y" symbols denote that a Data Quality Report exists for the atmospheric pressure measurement on those days. The lower-right inset shows part of the report obtained by clicking on the "Y" symbol for 3 March 2006.

intercomparison of different measurements of the same variable. Some key examples of VAPs aiding the quality assurance effort are described below.

Improvement of the downwelling diffuse shortwave measurement was accomplished through the creation and processing of the Diffuse Correction (DiffCorr) VAP. Research had shown that some downwelling diffuse shortwave measurements made with shaded Eppley-model precision spectral pyranometers (PSP) under clear-sky conditions fell below the physically-possible limit of diffuse irradiance as produced by a model incorporating both Rayleigh (molecular) scattering and conventional clear-sky atmospheric absorption [32]. Subsequent investigation [33, 34] attributed the problem to infrared loss from the pyranometer detector,

causing anomalously low shortwave readings, and a methodology was suggested [33] for correcting the measurements using information from co-located longwave pyrgeometer instruments. In implementing this methodology as a VAP [35], it was shown that the PSP infrared loss actually exhibits bimodal behavior in the pyrgeometer-pyranometer relationship, depending on ambient relative humidity conditions, and confirmed the earlier findings [34] that the daylight pyranometer infrared loss is enhanced compared to that exhibited at night. Thus, the DiffCorr VAP produced an improved measure of downwelling diffuse shortwave irradiance over what the instrument alone was capable of making by correcting for the infrared loss inherent in the raw measurements.
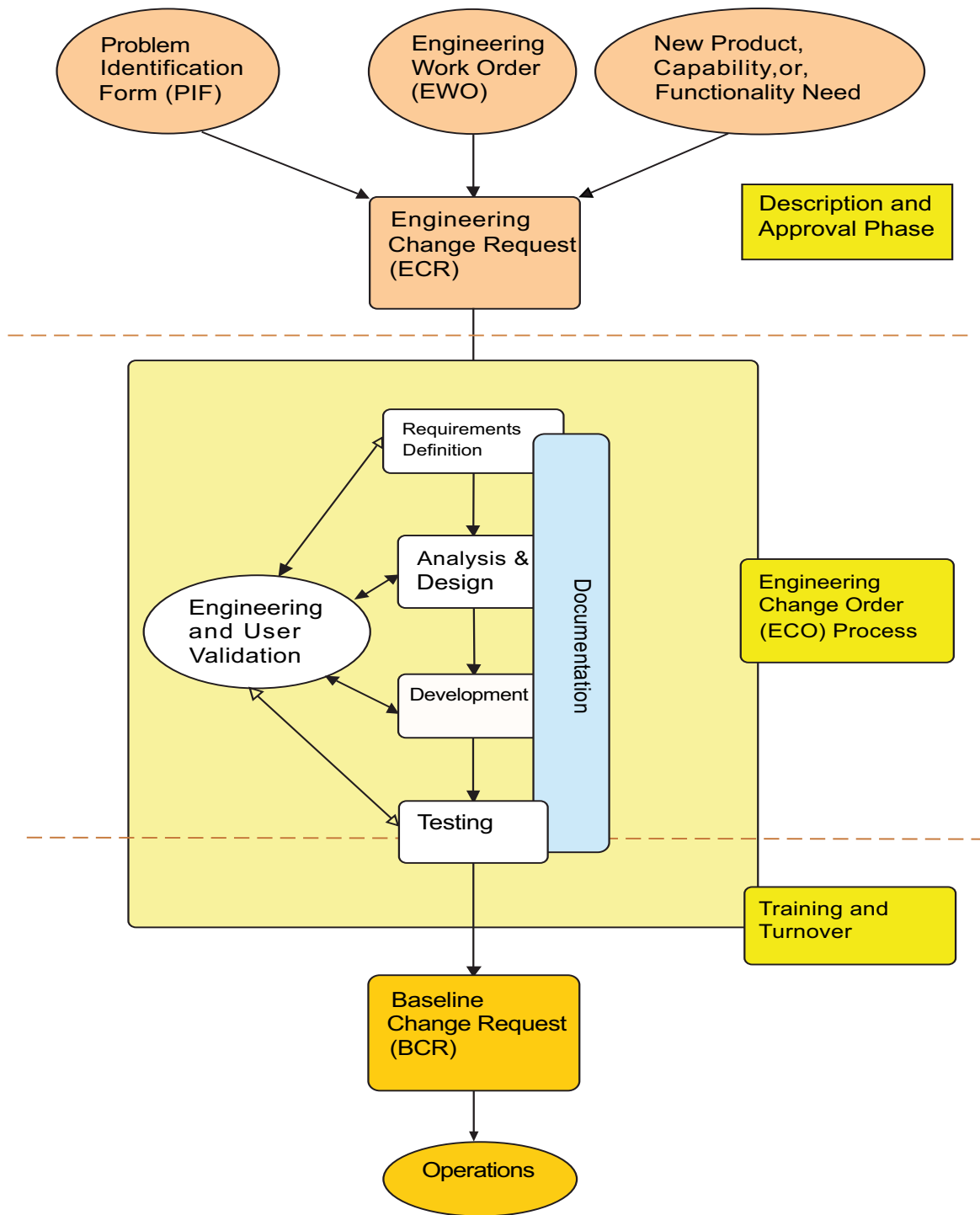
Fig. (10). ACRF engineering and operations management process flow.

Broadband irradiance measurement uncertainty has been addressed in another VAP. The Best Estimate Flux (BEFlux) VAP [36] was designed to produce the best possible measure of surface broadband irradiances for the Southern Great Plains Central Facility. Instrumentation there includes three separate surface radiation systems located within a few meters of one another. The BEFlux VAP compares these sets of like measurements for consistency and then averages the two that agree best to produce a best estimate for a value, if that agreement is determined to fall within typical limits estab-lished by the historical analysis of known good data. Such assessment of historical data then serves as an indication of what range of uncertainty field operations contribute to overall measurement uncertainty. This uncertainty information, when considered with other factors affecting measurement accuracy (e.g., calibration; sensitivity drift between calibrations; contamination of radiometer domes), can then be applied at single radiometer system sites to set limits on expected performance for quality assessment purposes.

Factoring in the range of climatologically-expected values at a particular locale has led to improved quality assessment of broadband radiometer behavior. The Quality Control of Radiation (QCRad) VAP [37] implements all that the ARM Program has learned during field operation about the behavior of surface broadband radiometers and the assessment of their data quality, while at the same time providing a best estimate of their radiation values for data users. For instance, in the development of the previously-described DiffCorr VAP, considerable effort was expended in the development of methods for testing downwelling longwave measurements, including analysis of pyrgeometer case and dome temperatures and detector fluxes, to prevent the use of questionable pyrgeometer values when correcting for infrared loss in the diffuse shortwave measurements. Earlier work for automated data quality assessment methodology has been implemented by the BSRN group [38]. Its methodology, which not only sets climatological limits but also makes extensive use of cross comparisons based on known relationships between variables, has been expanded and improved upon in the QCRad VAP. While the BSRN method uses limits that encompass the entire range of climates from the equator to the poles, the QCRad methodology uses limits based on the particular climatology of a given site, and includes additional tests based on knowledge gained through other VAP development efforts such as the aforementioned DiffCorr and BEFlux, plus also the Shortwave Flux Analysis VAP [39, 40]. VAPs in this case have played a role not only in testing measurements for quality but also in developing methods and expanding knowledge that can be used for improving the testing methodologies themselves.

Subtle measurement inaccuracies often defy detection through standard means such as limits testing or cross-measurement comparisons, and some measurements simply do not lend themselves to limits testing. In some cases there is no better test for subtle measurement inaccuracies than by using its data in scientific research. One example of this in the ARM Program has involved analysis of millimeter cloud radar data; its measured quantity is the reflected radiation from actively broadcast electromagnetic pulses. While the amount of power broadcast and returned can be monitored, there are many factors involved in the operation of this complex instrument that can affect data quality. The ARSCL (Active Remotely-Sensed Cloud Locations) VAP [41, 42] uses cloud radar data as its primary input, and it is within the ARSCL processing that many of the cloud radar measurement problems and operating characteristics have been revealed. ARSCL output serves as input to the Baseline Cloud Microphysical Retrievals (MicroBase) VAP [43], where results are scrutinized both in the context of whether retrievals are consistent with other measurements and also in their relevance to the physical circumstances in which they are embedded. Consideration of situational context is powerful for determining data quality to a degree not always possible when analyzing individual measurements or retrievals in isolation.

An example of a data quality finding totally unforeseen but discovered through the processing of several complex VAPs is described next. The Broadband Heating Rate Pro-

files (BBHRP) VAP [44] takes the output of the ARSCL and MicroBase VAPs and uses it in detailed radiative transfer model calculations. The BBHRP output is compared with surface and top-of-atmosphere irradiance measurements in a closure experiment framework. It has been determined through this ongoing model-measurement comparison that a subtle problem with Southern Great Plains Central Facility surface direct shortwave measurements was discovered. The comparison revealed a shift in model-measurement agreement statistics for the direct shortwave, which turned out to be caused by human error when two digits of the normal incidence pyrheliometer calibration factor were inadvertently transposed while being entered into a data logger. This human error resulted in a roughly two percent error in the direct shortwave measurements, which is within the stated uncertainty of the calibrations themselves [45] and as such was not detectable by standard limits and cross-comparison testing.

To summarize here, the processing of VAPs has and will continue to provide significant scientific value for ACRF data quality assurance efforts and for the climate science community at large. As described above, one way in which this happens relates to having just a single instrument making a measurement of a geophysical variable and the resulting challenge of identifying whether that measurement is indeed accurate. VAPs have been able to address this by routinely intercomparing different measurements of the same variable. As the example of the BEFlux VAP showed, measurements made by three virtually identical instrument systems allowed assessment of consistency and historical context when compared to past good observations. This approach has identified biases and temperature-dependent errors in various broadband radiometer systems that would have been extremely difficult to determine from a single radiometer alone, thus greatly improving the radiative flux dataset at the SGP ACRF.

A second way in which VAPs add scientific value is that they also, as illustrated by the MicroBase VAP example, retrieve or compute other geophysical parameters, from the raw observations, that are difficult to directly measure. One such example is ice water path (IWP). Analysis of this "higher order" product can then be used to identify issues in precursor datasets. For example, the ARM Program has produced IWP values using the MicroBase VAP for several years at different locations. If an analysis of the distribution of the IWP was markedly different for a current year as compared to previous years, this might indicate a problem with the millimeter cloud radar whose data are the input (*via* the ARSCL VAP) into MicroBase.

And finally, a third and novel way in which ARM Program VAPs add scientific value is through automated closure studies. The previously-described BBHRP VAP represents a significant closure study, wherein observations and retrievals of the atmospheric state, aerosol, and cloud properties are used to drive a radiative transfer model to compute the downwelling and upwelling longwave and shortwave radiative fluxes. These fluxes are compared against actual flux observations, and the differences are analyzed to investigate (a) the accuracy of the flux observations themselves, (b) the

accuracy of the radiative transfer model, and (c) the accuracy of the input data being used to drive the radiative transfer model. The radiative transfer model had been validated using a different closure study; thus, the BBHRP effort has allowed evaluation of the accuracy of the data used to drive the model.

12. ROLE OF FIELD CAMPAIGNS IN IMPROVING DATA QUALITY

ACRF sites host field campaigns to address specific scientific questions, augment routine data collections, and test and validate new instruments (http://www.arm.gov/acrf/fc.stm). Some of these campaigns are referred to within the ARM Program as intensive observation periods (IOPs). Through 2007, no less than 173 field campaigns have been carried out at the Southern Great Plains site; 18 have been held at Tropical Western Pacific sites; and 34 have been conducted at North Slope of Alaska sites. Additionally, 21 different campaign activities were held during the various mobile facility deployments through 2007. An emphasis of some campaigns has been on application of observational strategies and instrument deployments to improve the accuracy and quality of key ACRF measurements. A few of these are described here, which in some cases have had community-wide ramifications on field measurement characterization.

Given the importance of water vapor as a greenhouse gas and its role in the life cycle of clouds and precipitation, the transfer of latent and sensible heat, and atmospheric chemistry, the ARM Program has expended considerable observational effort, particularly at the Southern Great Plains site, on its measurement. Much progress has been made to this end through a series of water vapor IOPs, whose operations and science were summarized in [46]. These campaigns included three water vapor IOPs held in September 1996, September/October 1997, and September/October 2000, respectively, a lidar IOP held in September/October 1999, and the ARM-First International Satellite Cloud Climatology Project (ISCCP) Regional Experiment (FIRE) Water Vapor Experiment (AFWEX), conducted with NASA in November/December 2000.

The 1996 and 1997 water vapor IOPs and the 1999 lidar IOP provided key information on the quality and accuracy of on-site water vapor instrumentation [46]. Dual-radiosonde launches revealed significant variability across and within calibration batches and showed that differences between any two radiosondes act as an altitude-independent scale factor in the lower troposphere, such that a well-characterized reference can be used to reduce the variability. An approach subsequently was adopted by the ARM Program to scale the radiosonde's moisture profile to agree with the precipitable water vapor observed by the microwave radiometer; this scaling significantly reduced the sonde-to-sonde variability by a factor of two [47]. The first two water vapor IOPs also were able to verify that 60-m tower-mounted in-situ sensors can serve as an absolute measurement reference, and the site's unique Raman lidar can serve as a stable transfer standard; further IOP results found that the sensitivity of microwave radiometers was excellent over a wide range of integrated water vapor. Data from the 1997 IOP figured strongly in an effort to evaluate retrievals of column water vapor and liquid water amounts from microwave radiometers [48]. The third water vapor IOP in 2000 witnessed the fielding of further water vapor instrumentation to address remaining issues of absolute calibration.

Also beginning with the first water vapor IOP, verification of on-site humidity measurements was accomplished through laboratory intercomparison of in situ moisture sensors (including both capacitive chip and chilled mirror sensors) using Oklahoma Mesonet calibration facilities; tests were made both before and after the IOP, making it possible to detect instrument problems prior to the IOP and instrument failure or drift during the IOP [49]. Consequences of this work were modifications to humidity sensor calibration procedures and the fielding of redundant humidity and temperature sensors to better detect sensor drift and calibration error.

While the water vapor IOPs were concerned with characterization of water vapor in the lower troposphere, AFWEX attempted to better characterize the measurement of upper-tropospheric water vapor [50]. Results from the water vapor IOPs and AFWEX showed excellent agreement between satellite and Raman lidar observations of upper tropospheric humidity with systematic differences of about 10 percent; radiosondes, conversely, were found to be systematically drier by 40 percent relative to both satellite and lidar measurements [51]. Existing strategies for correcting the sonde dry bias were found inadequate in the upper troposphere and an alternative method was suggested that considerably improved sonde measurement agreement with lidar observations; it was recommended as a strategy to improve the quality of the global historical record of radiosonde water vapor observations during the satellite era. Further work was conducted to characterize the accuracy of Raman lidar water vapor measurements based on the results of the first two water vapor IOPs [52], while others have described the evaluation of daytime measurements of water vapor and aerosols made by the Raman lidar during an aerosol IOP conducted at the Southern Great Plains site in May 2003 [53].

Other field campaigns have helped characterize the measurement of atmospheric radiation. The second ARM Enhanced Shortwave Experiment (ARESE-II), conducted in February/April 2000 at the Southern Great Plains site [54], focused on broadband shortwave calibration using ground-based and aircraft-mounted radiometers and a standard. A diffuse horizontal shortwave irradiance IOP held in September/October 2001 at the Southern Great Plains site [55] characterized a nighttime offset by comparing diffuse irradiance measurements among most commercial pyranometers and some prototypes, with the goal of reducing the uncertainty of shortwave diffuse irradiance measurements in lieu of a standard or reference for the measurement. The first international pyrgeometer and absolute sky-scanning radiometer comparison held during September/October 1999 at the Southern Great Plains site [56] shed light on the reliability and consistency of atmospheric longwave radiation measurements and

calculations and determined their uncertainties, also in lieu of an existing absolute standard.

Much field work also has been done to improve the accuracy of the atmospheric emitted radiance interferometer's calibration; this instrument measures absolute infrared spectral radiance. It was the focus of an interferometer intercomparison IOP conducted at the North Slope of Alaska site from January 2004 through June 2006 [57]. Two instruments identical except in the blackbody temperatures used in their calibration were deployed. This comparison allowed for evaluation of the accuracy of the approach the ARM Program was using to correct for the non-linear behavior of the interferometer detector. Finally, during a spectral liquid and ice comparison IOP conducted at the Southern Great Plains site in October 2003, a second interferometer was deployed in a prototype rapid-sampling mode that allowed assessment of a newly-developed noise filter [58]. On the strength of this experiment, the ARM Program adopted the new rapid-sampling mode in all of its interferometers.

Finally, a more subtle understanding of how field campaigns contribute to data quality can be obtained by considering how well the collected data accomplish their scientific intent; this relates to the representativeness of the sites themselves for the desired measurement needs. The Nauru and Manus Island Tropical Western Pacific sites were established to make measurements representative of the surrounding oceanic area. A goal of the Nauru99 field campaign [59] was to investigate whether the small island, producing a cloud street phenomenon, was influencing measurements made there. The affirmative result then lead to a year-long Nauru Island Effects Study (NIES) in which a quantification of the island effect on measurements was made [60] and a method to detect the effect's ongoing occurrence and influence on collected data was developed [61]. This study also led to an explanation of the cloud street phenomenon [62]. While these activities are not data quality assessment in the traditional sense, they were able to quantify how well the measurements characterized the surrounding oceanic area, and more generally illustrate the importance of considering spatial scales as part of the quality assurance process for siting instrumentation to measure the intended target environment.

13. RECENT DIRECTIONS IN ACRF DATA QUALITY ASSURANCE

The ACRF data quality assurance program evolves as technologies avail themselves and the legacy data set grows. Three examples of how this is occurring are given here.

13.1. Use of the ACRF Time-Series to Improve Quality Control Limits and to Better Detect Trends

With 15 years of continuous data amassed for some measurements, a wealth of samples exists to conduct statistical analysis on specific time scales. Historical data are being mined [63] to identify site-specific and time-varying (monthly or seasonal) quality control flagging limits (Fig. **11**) and to facilitate better detection of subtle trends and abrupt changes in data (Fig. **12**) that are difficult to understand when not considered in a broader context. It is our goal

to incorporate departures from climatology as part of the quality assurance process for all data. Frequency distributions categorized by month and season should help establish better data range limits specific to those time periods. Time series that alert analysts to outliers should allow them to better distinguish bad data from unusual but valid data.

13.2. Improved Organization and Display of Data Quality Guidance

Data quality analysts need proper guidance on expected instrument performance and data characteristics when inspecting and assessing data. The large number of instruments fielded at ACRF sites require an analyst to gain a broad understanding of many concepts. To facilitate this activity, the Data Quality Office has developed a web-based Wiki system to provide consolidated, interactive access to data quality guidance [64].

A Wiki is a collaborative platform designed to allow multiple users the ability to edit web pages from any computer. It is organized in an open format viewable from a web browser and is easily updatable by any qualified, registered user. Changes made are viewable instantaneously without the assistance of a central web designer, allowing both the rapid addition of new information and the updating of outdated information, all the while preserving revision history. The open-source Twiki platform[1] was selected for storing ACRF data quality guidance. Basic instrument performance information and data quality guidance have been assembled and transformed into individual-instrument Wiki guidance pages (Fig. **13**). This information includes visual examples of both good data and known problems. By having a repository of examples and accompanying explanations, analysts are able to acquire pattern-recognition skills and use them to scan data plots more efficiently, allowing them to more accurately identify problems. This decreases the amount of time spent inspecting data and leads to quicker problem identification and reporting, which in turns leads to faster problem resolution. The Wiki also allows for open exchanges of ideas on data quality, and has streamlined the training of new analysts by more easily storing and propagating institutional knowledge.

13.3. New Operations Status Database

To better track and report the status of ACRF instruments and their subcomponents at widely distributed locations, operations staff recently implemented a comprehensive operations status system database. By serving as a central collection point for all ACRF instrument status information, the system is enabling timely and cost-effective decision making affecting site operations, particularly with respect to addressing instrument performance issues, and in doing so is becoming a key component of the data quality assurance process.

The database brings together and keeps track of information describing many activities common across the sites but that was documented in disparate locations; this information encompasses calibrations, preventative and corrective maintenance, shipping and receiving, and inventory. It also pro-

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[1] http://www.twiki.org/
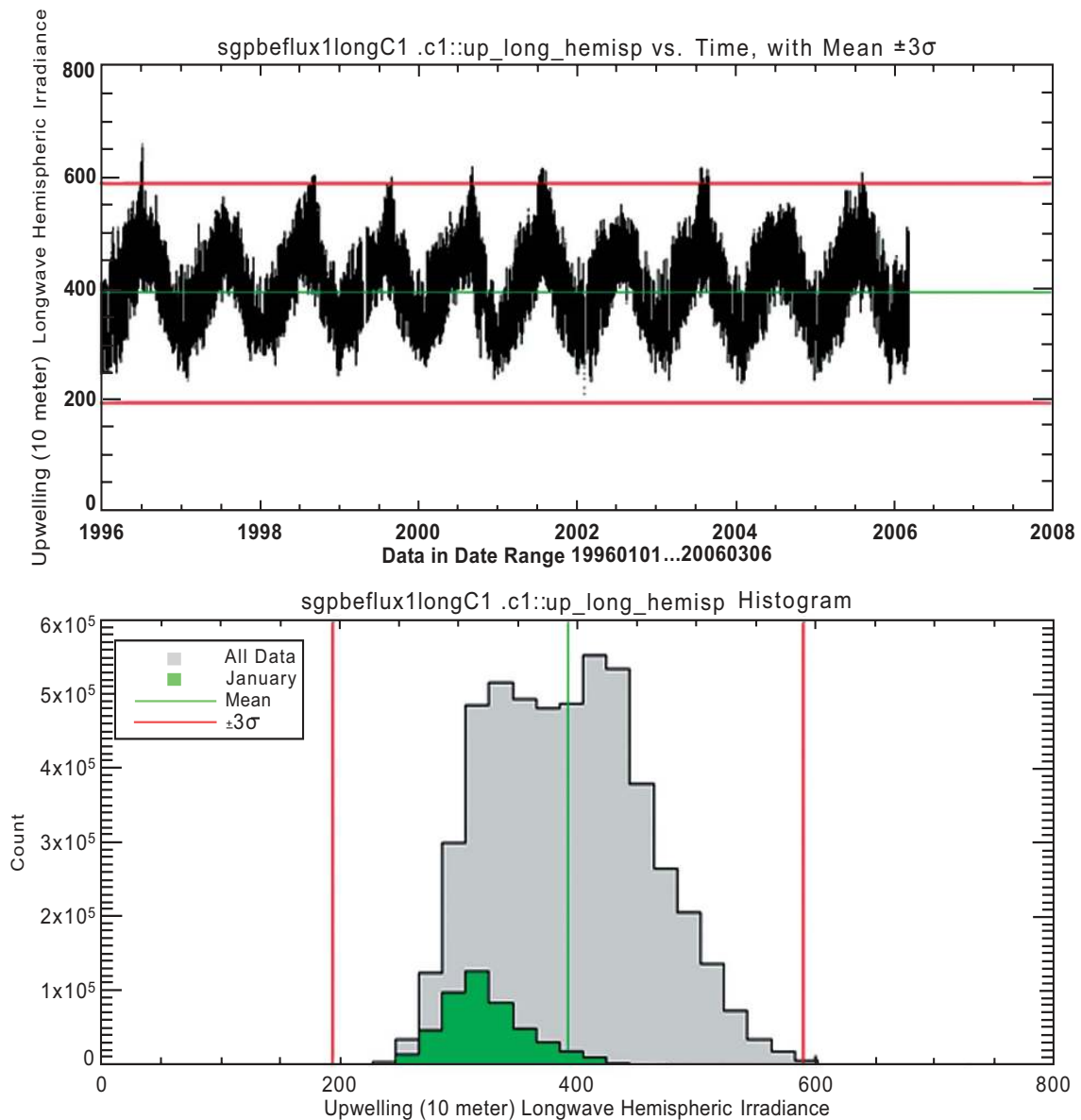
Fig. (11). Upwelling longwave radiation exhibits strong seasonal dependence, seen in its time-series (top) and frequency distribution (bottom). The gray area represents the frequency distribution of all months while the green area displays values for January for the ten years analyzed. Mean (green) and 3 standard deviation limits (red) are shown for all months. As can be inferred, precise limits for a valid data range in January would be more restrictive than those for an entire year.

vides consistent time stamping for tracking these activities and for measuring the length of time a system or component spends in a given operational state. The database is proving useful for identifying chronically-underperforming instruments and components.

14. SUMMARY

The ARM Climate Research Facility data quality assurance program is a collaborative, multi-laboratory, multi-university effort to produce a research quality data set for use not only by ARM Program-funded scientists but also by the climate research community at large. Fig. (**14**) displays key components of this program, which are summarized in conclusion here.

Instruments deployed at ACRF sites have been selected to satisfy specific measurement requirements identified to achieve the scientific goals of the ARM Program. An instrument mentor serves as the technical point of contact for each instrument; he or she develops and documents a fundamental statement of expectations for the performance of the instrument so that data users can determine the suitability of its measurements for their scientific application. The mentor provides site operators with detailed guidance and training for deploying and maintaining the instrumentation. Mentors also prepare data quality inspection and assessment guidance for use by data quality analysts and prepare monthly data analysis retrospectives describing instrument performance. ACRF site operators and technicians put into
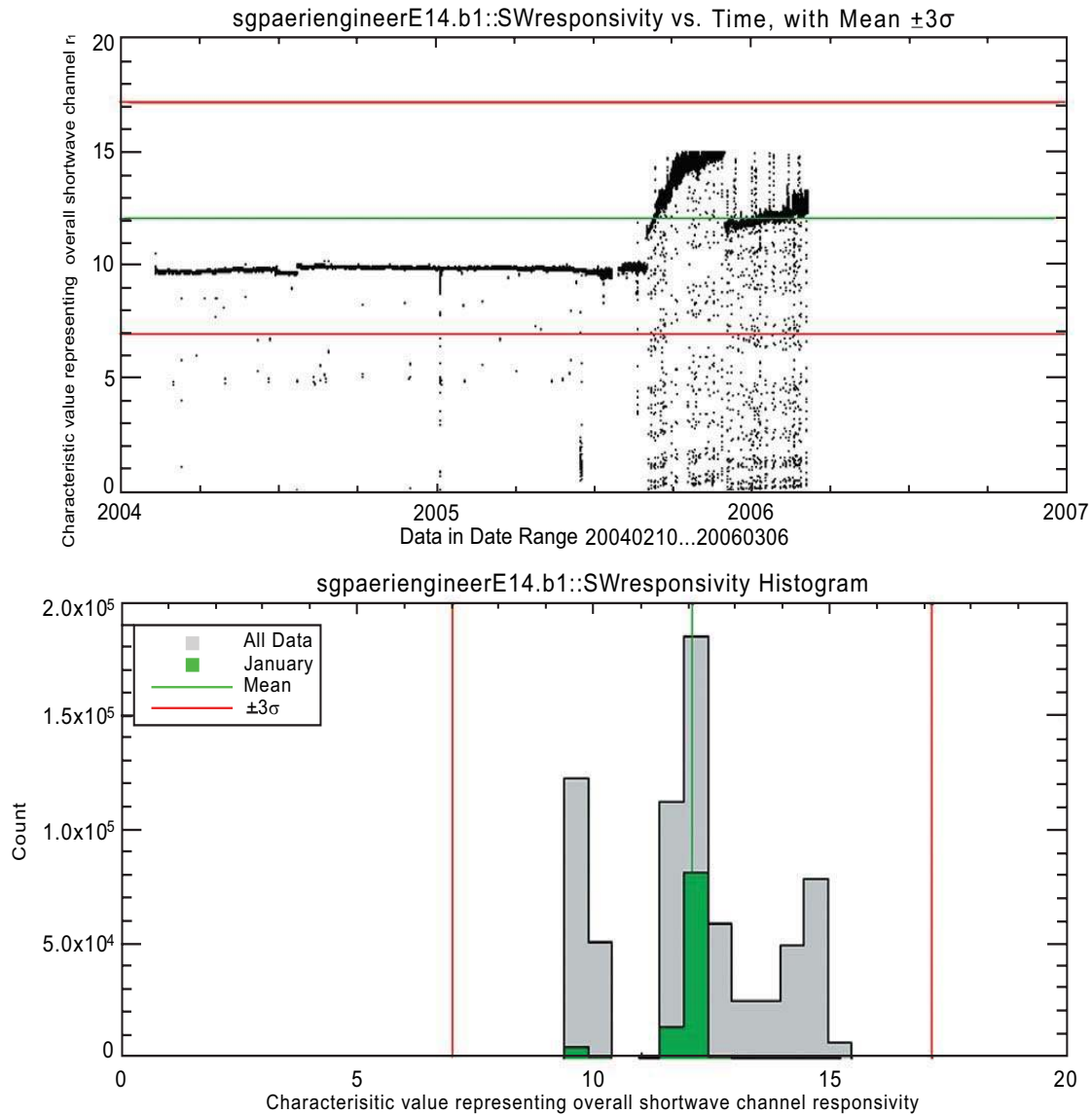
Fig. (12). A significant shift is detected in the time series (top) of a diagnostic engineering parameter within the Atmospherically-Emitted Radiance Interferometer during the second half of 2005. A multi-modal distribution is produced (bottom), with the gray area representing the frequency distribution of all months and the green area representing that for January for the two years analyzed. Mean (green) and 3 standard deviation limits (red) are shown for all months.

place the prescribed preventative and corrective maintenance procedures and collect and store information describing the results of their efforts.

A data collection and processing infrastructure has been developed to efficiently transport the data generated by instruments in the field to a central distribution point. Through several iterations and significant efforts to establish Internet connectivity to each field site, the ACRF data system has developed an efficient data flow process that tracks data integrity and timeliness from the instrument system to the central distribution point and ultimately to the Data Archive. Data from all field sites are centrally processed on an hourly

basis, accomplished through the use of satellite networking, specialized data movement processes, and a tight configuration management process. This rapid transfer of data allows for first-level evaluation of data quality for most ACRF data streams in the near real-time, which is important since data are made available at the Data Archive to the general public within a few days of collection.

Data quality inspection and assessment activities have evolved over the life of the ARM Program, culminating in the development of comprehensive inspection, assessment, and reporting tools. Data quality analysts use the guidance provided by instrument mentors to routinely inspect, assess,
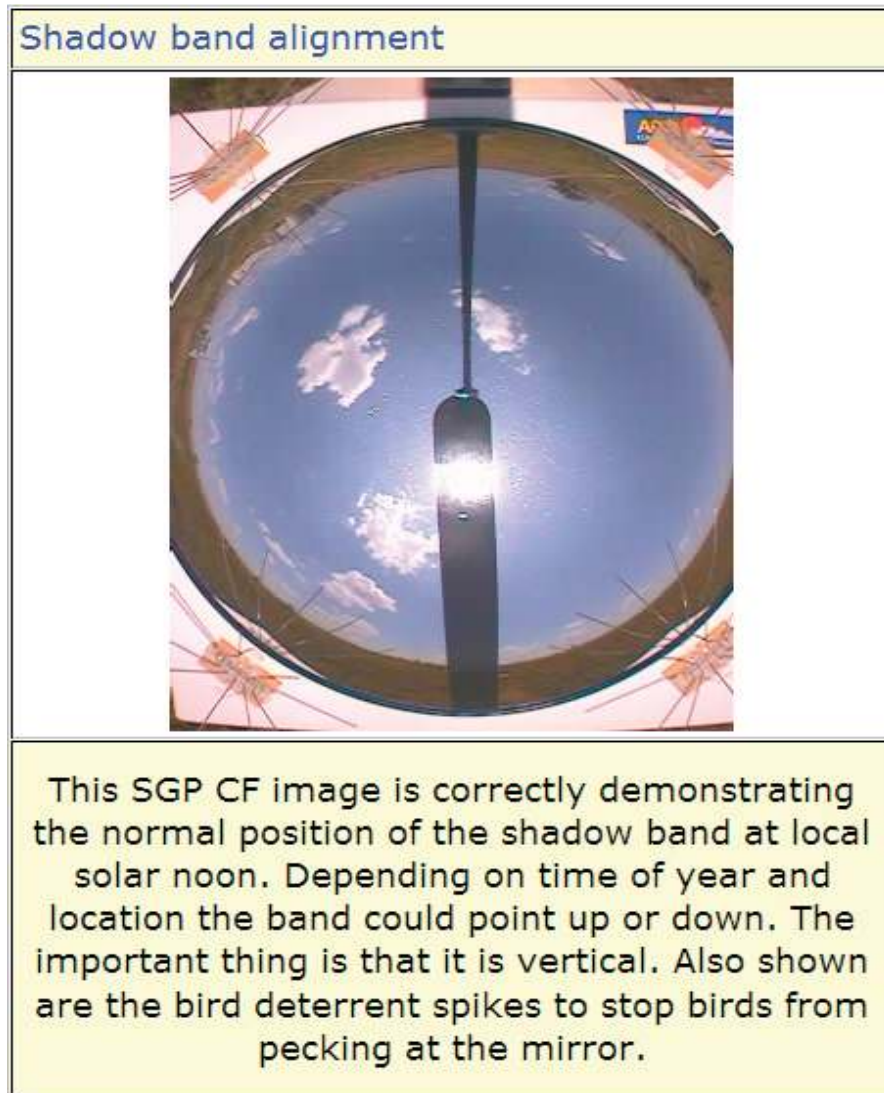
Fig. (13). Data Quality Wiki example for the Total Sky Imager showing proper shadowband alignment at local solar noon, an optimal time to make this check. The "optimal" image can be compared by data quality analysts to real-time examples as a pattern-recognition technique.

and report on data quality, and they initiate the problem resolution process. Instrument mentors provide in-depth guidance for this activity and lead the problem resolution process. Site scientists provide a broad perspective on data quality and oversee problem resolution at their site. They also interact with the scientific community to plan and conduct field campaigns.

To make data easy to obtain and sufficiently intuitive to work with, the Data Archive efficiently stores and provides access to the data collected by field instrumentation and presents specific and complete quality information for all data files. Data stream reprocessing is conducted whenever it becomes necessary to remove known, correctable problems, helping to produce a consistent data format across sites and time to further increase data usability. Engineering and operations management processes help ensure optimal instrument and systems performance and makes sure that fundamental changes are conducted in a structured manner.

The scientific value of ACRF measurements has been improved through the processing and analysis of value-added data products. These new data sets provide sophisticated interpretations of measurement-level information and data quality not possible through routine data analysis. Field campaigns that have applied observational strategies and instrument deployments aimed specifically at better measurement characterization also have led to improved data quality.

A comprehensive, end-to-end data quality assurance program is essential for producing a high-quality research data set from observations made by automated weather and climate networks. The processes developed by the ARM Program offer a framework for use by other instrumentation- and geographically-diverse networks, and have been described here to highlight the myriad aspects that go into such an effort. We invite community appraisal of these processes so that we may continue to improve them, and also invite your findings on ACRF data quality so that we can continue to improve the legacy data set. These comments and findings may be sent to armdataquality@arm.gov.
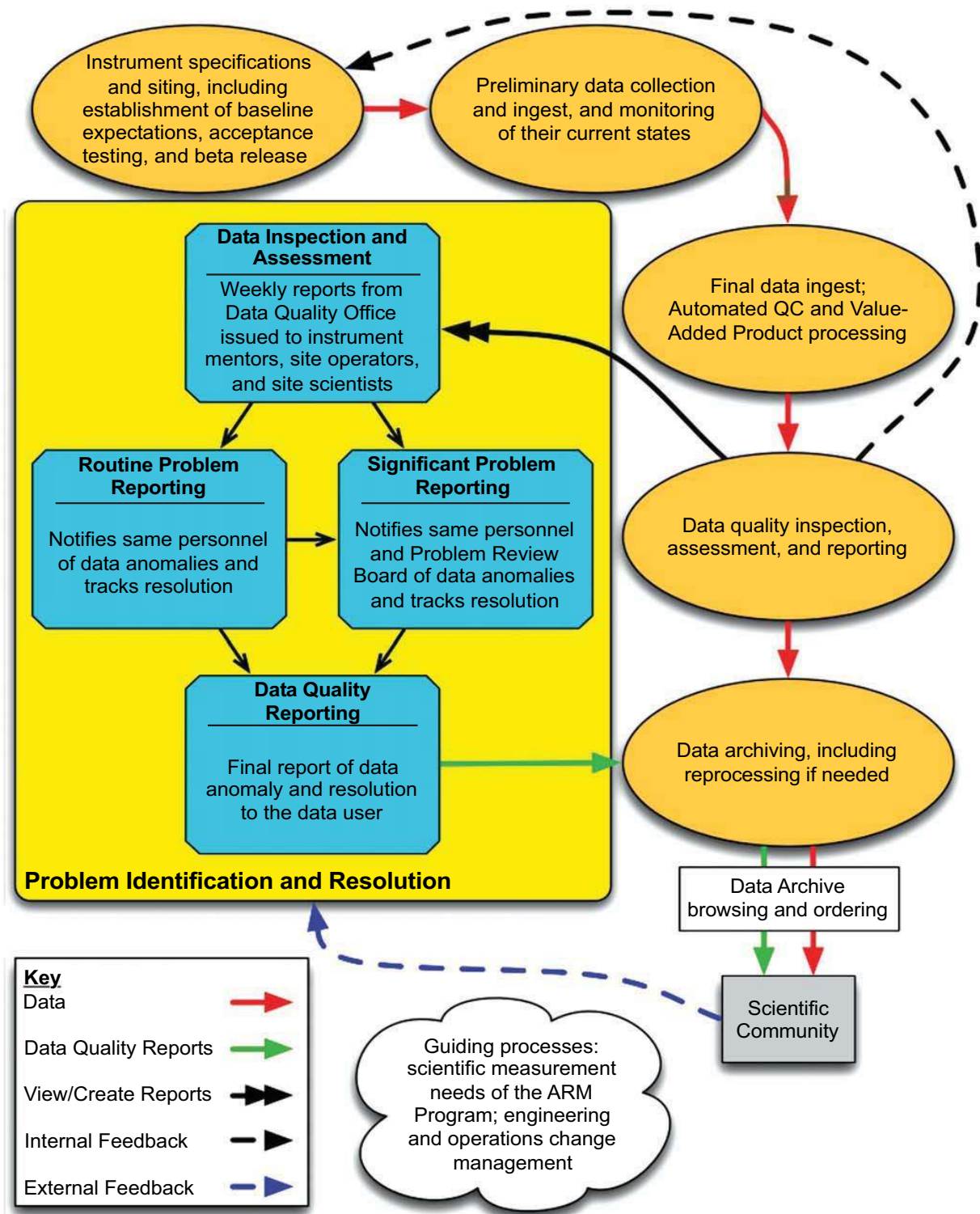
Fig. (14). Flow chart summarizing key elements of the data quality assurance process.

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