First Year Progress Report, *Developing a Climate Data Record for Total and Spectral Solar Irradiance*
NOAA Award Number NA09NES4400016
National Environmental Satellite Data and Information Service Program Office (NESDISPO)
Reporting Period: 08/01/2009 - 01/31/2010
Principal Investigator: Peter Pilewskie, Laboratory for Atmospheric and Space Physics, University of Colorado

The primary objective of this program is to develop baseline Climate Data Records (CDR) spectral and total solar irradiance. To accomplish the tasks set forth in the proposal, we are assembling a Solar Irradiance Product Development from investigators at the University of Colorado Laboratory for Atmospheric and Space Physics (LASP), the Naval Research Laboratory (NRL), and the National Institute for Standards and Technology (NIST). The purpose of the TSIS CDR Product Development Team is to ensure the establishment an accurate baseline solar irradiance CDR to enable the rapid and reliable generation of solar irradiance Climate Data Records following the launch of the Total and Spectral Solar Irradiance sensor (TSIS) later this decade. This team will also insure data stewardship of total solar irradiance (TSI) and solar spectral irradiance (SSI) through the development of the TSIS Algorithm Theoretical Basis Document (ATBD); CDR development from current and heritage satellite instruments; construction of irradiance composites; and development of solar irradiance products and algorithms to be distributed to the broader community. The team will advise both NOAA and the LASP TISIS development team on the calibration effort and review the documentation associated with this plan. Finally, the CDR Product Development Team will quantify relationships between irradiance with various types of solar activity indicators.

NOAA funding for NRL and NIST is via direct distribution. At the time of this report neither of these collaborators has been funded although both are reporting that the final details for direct distributions are being worked out so our hope is that this happen soon. Because of this delay, some of the proposed tasks under this proposal have yet to be initiated.

The primary focus through the first 6-months has been on developing radiative transfer models for quantifying the atmospheric heating response to observed solar spectral variability. Because of the highly spectrally varying behavior of absorption and scattering in Earth's atmosphere, the spectral distribution of the Sun's radiative energy and its variance is important for quantifying Earth's radiation budget and the vertically resolved deposition of solar energy in the atmosphere, and for resolving the mechanisms of climate response to solar forcing. The MODTRAN4 radiative transfer model was run under varying levels of solar activity with varying spectral irradiance as observed from the Spectral Irradiance Monitor (SIM) flying on the NASA Solar Radiation and Climate experiment (SORCE). Initial results indicate that for active states heating is enhanced in the upper stratosphere and mesosphere due to ozone absorption in the Herzberg continuum and Hartley-Huggins bands (220-320 nm). However, bright plage-dominated activity results more heating in the lower stratospheric UV bands due to ozone absorption in the Chappuis band (450-600 nm), while darker sunspot cases exhibits less heating in this region of the atmosphere.

Similar variability is seen in the lower troposphere due to water vapor near-infrared bands: for the sunspot cases, heating is reduced across the entire near-infrared spectral region, opposite to the

enhanced heating for plage, until about 1200 nm, where the trend is reversed. The band-integrated vertical profiles of instantaneous heating difference show that the net impacts are reduced (increased) heating in the troposphere and stratosphere for sunspots (plage) compared to the quiet Sun state. The opposing behavior due to ozone across the ultraviolet and visible for the sunspot case reduces the stratospheric cooling trend.

Current work is to extend these model runs to cover all latitudes and solar geometries. Using 13 solar activity cases we are building global (latitudinal) maps of diurnally averaged solar spectral heating rate differences between high activity states and representative quiescent states. The ultimate goal is to determine solar cycle spectral variability and its climate impacts, an overarching objective of this CDR development team,

Because this report covers only the first 6- months of this grant (and funding has been available for just four) there have been no peer-reviewed publications or conference presentations. However, with our collaborators coming online soon and our activities ramping up we anticipate a very productive first full year; we will present papers at two conference proceedings this fiscal year.

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Principal Investigator: Peter Pilewskie, Laboratory for Atmospheric and Space Physics, University of Colorado

The primary objective of this program is to develop baseline Climate Data Records (CDR) spectral and total solar irradiance. To accomplish the tasks set forth in the proposal, we are assembling a Solar Irradiance Product Development from investigators at the University of Colorado Laboratory for Atmospheric and Space Physics (LASP), the Naval Research Laboratory (NRL), and the National Institute for Standards and Technology (NIST). The purpose of the TSIS CDR Product Development Team is to ensure the establishment an accurate baseline solar irradiance CDR to enable the rapid and reliable generation of solar irradiance Climate Data Records following the launch of the Total and Spectral Solar Irradiance sensor (TSIS) later this decade. This team will also insure data stewardship of total solar irradiance (TSI) and solar spectral irradiance (SSI) through the development of the TSIS Algorithm Theoretical Basis Document (ATBD); CDR development from current and heritage satellite instruments; construction of irradiance composites; and development of solar irradiance products and algorithms to be distributed to the broader community. The team will advise both NOAA and the LASP TISIS development team on the calibration effort and review the documentation associated with this plan. Finally, the CDR Product Development Team will quantify relationships between irradiance with various types of solar activity indicators.

NOAA funding for NRL and NIST is via direct distribution. At the time of this report both collaborators' funding has been established or is imminent. Because of this delay, the schedule for LASP tasks has been shifted to coincide with the 3-year schedules of NRL and NIST. Thus, we anticipate that this is a three year program commencing in August, 2010. Nevertheless, we have initiated work that is described below.

During the second 6-months reporting period for this program we continued work on the development of radiative transfer models for quantifying the atmospheric heating response to observed solar spectral variability. The specific emphasis was on determining spectral heating rate profiles for a simulation of SORCE Solar Irradiance monitor (SIM) observed solar cycle variability from 2004-2008. The objective was to quantify radiative impact due to spectral variability. The climatic impact was reported by *Merkel et al.* [2010] at the SORCE Science Meeting in June, 2010.

We have initiated discussion with Derek Yu on developing the System Architecture Plan for TSIS. Slides relevant to the TSIS data flow and the SORCE data processing which provided the general structure for TSIS processing are attached.

Outline

- Existing TIM and SIM Data Systems
  - SORCE Data Processing System
  - Glory TIM Data Processing System
- TSIS Data System Concept

SORCE TIM and SIM Data System

- All data processing is performed at the SORCE Science Operations Center (SOC) at LASP in Boulder, Colorado, USA
  - Process, manage, analyze, and distribute science data products
  - Facilitate scientific analysis of algorithms, calibration data, and data products
  - Reprocessing of entire mission when algorithms or calibrations are updated
  - Maintain all software, calibration data, science data products, and other information under strict configuration control
  - Conduct formal versioned software releases and maintain unique data product versions for each instrument
  - Maintain traceability between software, calibration data, data products, and production job parameters
  - Routinely deliver processed science products to the NASA GES DISC and provide interactive data access on the SORCE web site
  - Data Backup and Archival
  - Retain all data products online for the life of the mission, demoting only data that are more than two versions old

SORCE Data Processing Background

- Algorithm Theoretical Basis Document (ATBD)
  - Algorithms to produce science data products were implemented as described in the SORCE Algorithm Theoretical Basis Document (ATBD)
  - Note that the SORCE ATBD is being updated for TSIS
- Processing and Release Timeline
  - SORCE science processing takes place within 1-7 days of data reception from the spacecraft
  - Preliminary data products can be processed within 24 hours
  - Finished data products are computed and released within one week
    - 7-day delay ensures that we have the NORAD ephemerides which are required for solar distance and Doppler corrections

SORCE Data Products and Availability

- Level 3 Science Products
  - Total Solar Irradiance (TSI)
    - Daily releases of TSI data to NASA GSFC Earth Sciences DISC
    - Daily releases to SORCE web site
    - Daily and 6-hourly averages, in ASCII format
  - Solar Spectral Irradiance (SSI)
    - Daily mean spectra
    - Releases at semi-regular intervals as software and calibration updates become available. About twice per year for each instrument.
    - Nominal daily releases with preliminary (e.g. extrapolated) calibrations/corrections
  - Periodic releases of data with definitive calibrations/corrections
- Intermediate Science Products (Level 1 and Level 2)
  - Higher time-cadence data are produced, but not delivered as standard products
  - Available in collaboration with instrument science team

Data Processing System Updates

- In order to maintain science data accuracy, gathering and analysis of in-flight instrument calibration data is necessary and ongoing
- TIM
  - Data processing system is currently producing version 10 science data products
  - Routine Enhancements
    - Updated servo gain calibration
    - Updated degradation correction
    - Updated dark correction
- SIM
  - Data processing system is currently producing version 17 science data products.
  - Routine Enhancements
    - Updated degradation correction
    - Updated profile integral calibration
    - Wavelength shift corrections

Processing Algorithm Maturity and Design

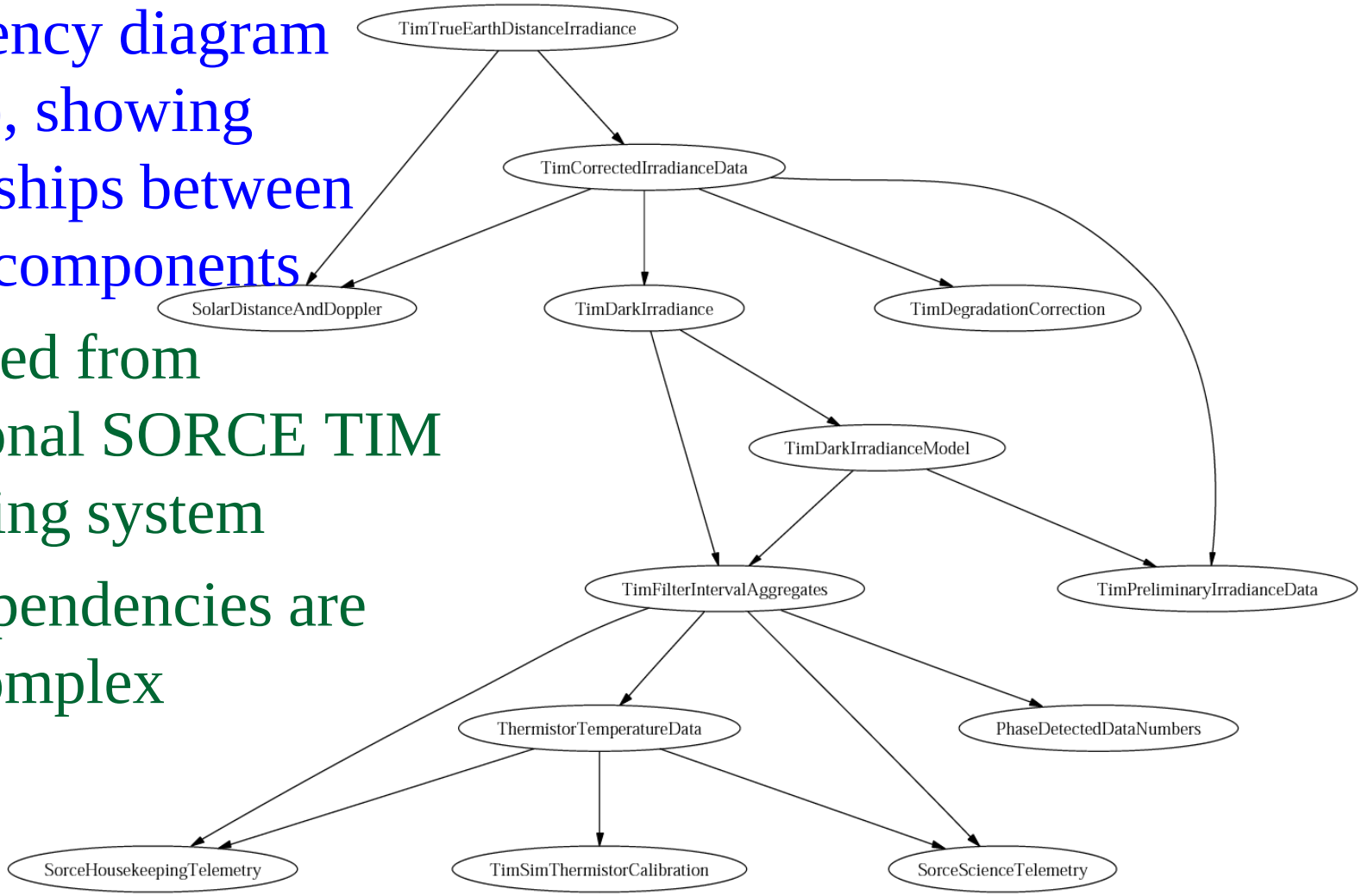
- TIM and SIM Science Processing Software is mature and reliable
- TIM and SIM Science Processing Algorithms
  - Algorithms are based on the representative “Measurement Equation”
    - Describes the variables required to produce Total and Spectral Solar Irradiance
    - Presented in the ATBD, to be updated for TSIS
  - Some TIM and SIM algorithms are common/shared (SIM ESR processing)
- SORCE Design Motivation
  - Anticipation of change
    - Changes / updates to algorithms, software, and calibration data
    - Minimize subsystem “coupling” to reduce impact of even substantial changes
  - Frequent Reprocessing (a few times per year)
  - Long-term accessibility and reproducibility of data (post mission)
- SORCE Design Choices
  - Object-Oriented s/w design, Centralized I/O functionality, Exception Handling
  - Storage of data in a commercial relational database system

Data Processing Operations

- Processing occurs for each complete calendar day (UTC)
- Processing Streams
  - One automated daily processing stream per instrument
    - Automatically initiated daily following telemetry downlink/availability
- Data “sub-products” and versions
  - Modular software components feed into each measurement equation term
  - Data processing algorithms are triggered by other algorithms, as required
  - Key “sub-products” are stored to facilitate analysis and diagnostics
  - All products and “sub-products” are versioned to facilitate traceability
  - A new set of products with a unique version is generated for each reprocessing
- Reprocessing
  - Entire mission is reprocessed (per instrument) when updated calibrations or algorithms are introduced
  - Ensures quality and consistency of science products
  - Performed as needed. Typically twice a year to incorporate improved characterization of instrument degradation
  - For reduced reprocessing time, runs in parallel on multiple computers via a distributed processing management system (Condor)

TIM Science Processing Software Architecture

- Software module dependency diagram (partial), showing relationships between system components
- Generated from operational SORCE TIM processing system
- SIM dependencies are more complex



SORCE Post-Launch Changes

- Software Updates
  - TIM
    - 73 of 93 software modules updated (not all affected data quality)
  - SIM
    - 157 of 245 software modules updated (not all affect data quality)
  - Common/shared Software
    - 35 of 85 software modules updated (not all affect data quality)
- Calibration Data Updates
  - Based on either in-flight characterization or improvements to ground-based measurements
  - TIM
    - 6 of 10 calibration sets updated
  - SIM
    - 10 of 19 calibration sets updated

Glory TIM Processing

- The Glory TIM Science Data System is a simple adaptation of the fully operational data system currently running for the SORCE TIM instrument
- All data processing will occur locally at LASP in Boulder, Colorado at the TIM Science Operations Center (SOC).
- System will process, manage, analyze, and distribute data products
- TSI data products generated within 5 days of reception
- All data products retained online for the life of the mission
- Algorithms for Glory TIM are inherited from SORCE which are developed from the SORCE ATBD
- Software and Data Configuration Management procedures identical to SORCE and are already in place
- Most software items are shared with SORCE

Software Reuse – Glory TIM Example

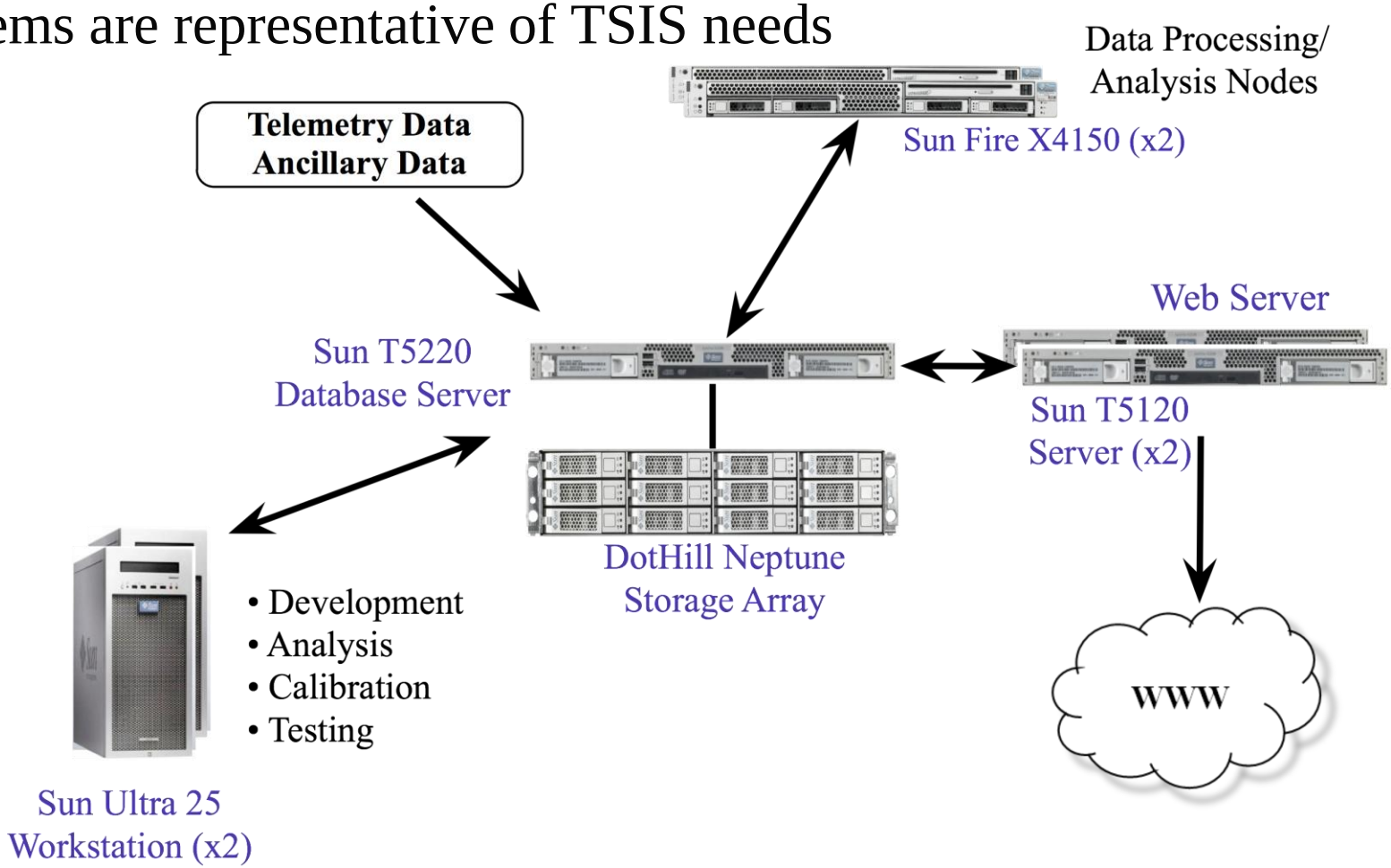
- Some code adaptation is required to generalize the SORCE routines for reuse on TSIS.
- We maintain one code base, with distinct configuration management procedures for each mission, as needed
- Example: Reuse from SORCE TIM for Glory TIM:
  - Total compiled lines of code (no comments): ~72000
  - Total SORCE TIM software packages: 95
    - Most packages contain approx. 5 classes
  - Number of software packages to be
    - Reused: 80
    - Modified / Generalized 15
    - New: 1

Implementation Notes

- The TSIS data processing system is very closely based on the SORCE and Glory data processing systems, and would share a large fraction of the SORCE & Glory code
  - The SORCE data processing system is fully operational and producing a full compliment of data products on a daily basis
  - Successful, low-cost adaptation of original SORCE system for Glory
- Software and Data Configuration Management procedures are already in place, including:
  - Revision control and problem tracking systems.
  - Change approval/review procedures.
  - Data configuration management (data versioning) is built-in to the science processing software system.
- SORCE and TSIS software requirements and algorithms are nearly identical.
  - Extensive code reuse from SORCE (some generalizations are req'd).
  - Some additions for mission unique aspects
  - Existing software libraries can be leveraged

Science Processing Computer Architecture

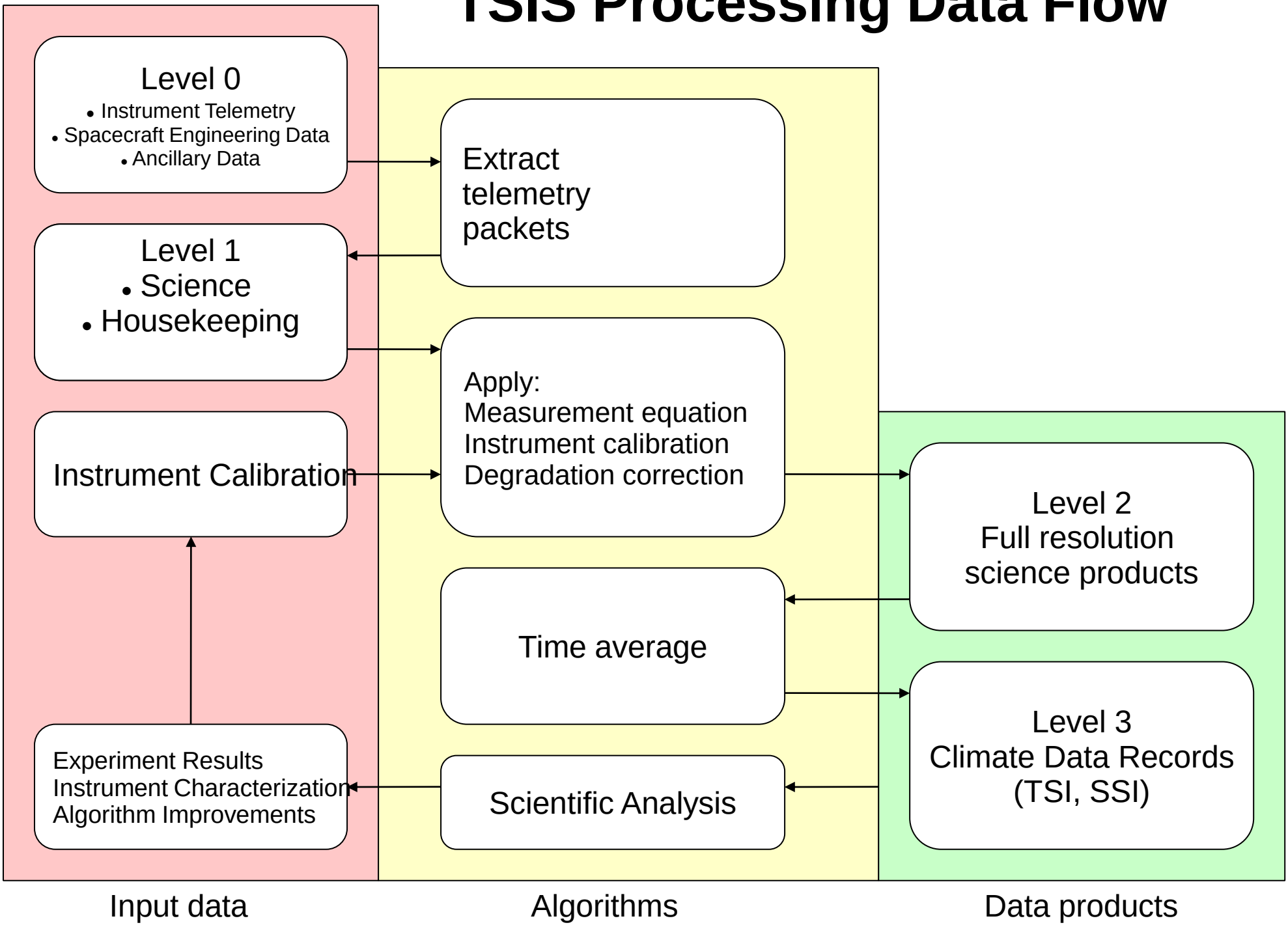
- Science processing and dissemination computer architecture utilizes a modest set of computer systems and storage hardware
- Characteristic systems used by SORCE and Glory TIM processing systems are representative of TSIS needs



Summary

- SORCE system has proven robust and flexible to algorithm updates. The impact of updates on unrelated software has been minimal, owing to the data-centric object-oriented design.
- Maintaining Data Quality
  - Post-launch algorithm, software, and calibration maintenance are vital
    - Analysis of on-orbit characterization data
    - Re-analysis of ground-based characterization data
    - Updates to algorithms and software
  - Testing and Validation of software and calibration updates
- To ensure quality data products, instrument providers need to be involved throughout the software development and post-launch operations and software maintenance processes
  - This option represents the lowest risk to TSIS and the highest probability of maintaining the Solar Irradiance Climate Data Record and thus it is sound Science Data Stewardship.

TSIS Processing Data Flow



Data Volumes

- SORCE Total Irradiance Monitor (TIM)
  - Total Solar Irradiance
  - Produces 20 MB/day

- SORCE Spectral Irradiance Monitor (SIM)
  - Solar Spectral Irradiance
  - Produces 30 MB/day

Computational Requirements

Commodity Linux box, dual core, 4GB RAM

(plus database server, web server)

- SORCE TIM TSI
  - 18 minutes/day
- SORCE SIM SSI
  - 10 minutes/day