The mission operations system for Wide-field Infrared Survey Explorer (WISE)

Ingolf Heinrichsen[1]

[1]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, CA 91109;

ABSTRACT

The goal of the Wide-field Infrared Survey Explorer (WISE) mission is to perform a highly sensitive all-sky survey in 4 wavebands from 3 to 25µm. Launched on a Delta II rocket into a 500km Sun-synchronous orbit in June 2009, during its 7 months of operations, WISE will acquire about 50GBytes of raw science data every day, which will be down-linked via the TDRSS relay satellite system and processed into an astronomical catalogue and image atlas.

The WISE mission operations system is being implemented in collaboration between UCLA, JPL and IPAC (Caltech). In this paper we describe the challenges to manage a high data rate, cryogenic, low earth-orbit mission; maintaining safe on-orbit operations, fast anomaly recoveries (mandated by the desire to provide complete sky coverage in a limited lifetime), production and dissemination of high quality science products, given the constraints imposed by funding profiles for small space missions.

Keywords: Infrared Astronomy, Mission Operations Systems, Science Data Processing, All-sky Survey

1. THE SCIENTIFIC GOALS OF THE WISE MISSION

The Wide-field Infrared Survey Explorer (WISE) mission will perform a highly sensitive all-sky survey in 4 wavebands from 3 to 25µm. More than two decades ago in 1983 the InfraRed Astronomy Satellite (IRAS) gave us what is still our best view of the mid–infrared sky so far. WISE will map the entire sky with resolution comparable to the few square degrees shown here, achieving 500 times better sensitivity

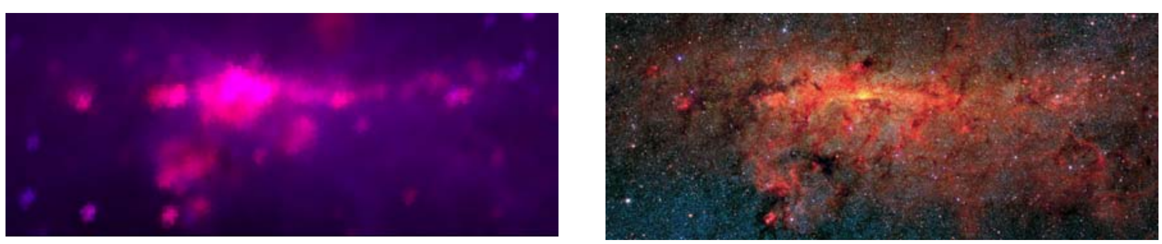

Figure 1 - Comparison of the expected improvement in resolution of WISE as compared to IRAS

than IRAS (Figure 1).

As an all sky survey WISE is well suited to influence a wide variety of astronomical research and look for the superlative objects of a given class like the most luminous galaxies or the nearest stars. (*Ref. 8, 9, 10*).

The WISE data products will provide new insights into many fields by providing:

- The radiometric diameters and albedos for most known asteroids
- The space density, mass function, and formation history of brown dwarf stars in the solar neighborhood including the closest stars to the Sun
- Insight into the evolution of circumstellar dust and debris disks.
- Observations of the very faint end of the luminosity function of protostars in nearby star formation regions.
- Images of the IR morphologies for thousands of nearby galaxies

- Maps of clusters of galaxies and large scale structure within 7-billion light years
- The nature of and evolutionary history of ultra-luminous infrared galaxies forming the most luminous galaxies in the Universe

WISE will also provide an enduring source catalogue with unprecedented sensitivity over the entire sky that will allow astronomers to better plan observations and exploit upcoming missions like JWST.

2. THE WISE FLIGHT SYSTEM

The WISE Flight System has been described extensively in several other publications (*Ref. 1, 2, 3*). We will therefore only provide a short summary emphasizing hardware design features relevant to the in flight operations of WISE.

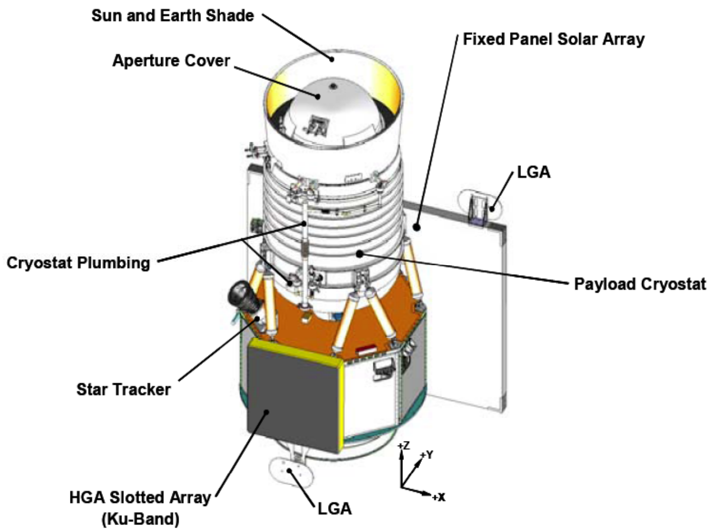

Figure 2 - The WISE Flight System

3.1 The WISE Spacecraft

WISE is a single string spacecraft based on Ball Aerospace & Technologies Corporation's (BATC) RS300 bus architecture, which has a modular design well suited for this type of low earth orbit short lived mission (7 months), providing a stable pointing and scanning platform as well as power, communications and fault protection. The basic layout of the WISE flight system is shown in Figure 2.

The high gain antenna, which is used to communicate the science data to the ground at a rate of 100Mbits/s, is body fixed, which means in order to communicate the entire spacecraft has to be re-oriented to allow downlinks via the TDRSS relay satellites, posing special requirements on WISE operations (Section 4). Two low gain antennas provide command and housekeeping telemetry of 4 or 16 kbits/s. 100% coverage can be achieved during critical events or contingencies using two Tracking and Data Relay Satellite System (TDRSS) relay satellites for any given orientation of the WISE flight system.

3.2 The WISE Payload

The WISE payload provides a 40-cm-diameter afocal telescope, providing a resolution of 5" (10" at 23µm) with a 47 arcmin instantaneous field of view, a scan mirror, and two 2-band reimaging cameras, all contained within a two-stage solid-hydrogen cryostat. Data is taken simultaneously in all 4 infrared wavelengths: 3.3, 4.7, 12 and 23µm. The instrument will utilize 1024x1024 detector arrays which reach sensitivity limits of 120, 160, 650, and 2600µJy at 3.3, 4.7, 12, and 23µm respectively. The operating temperatures will be 30-34K for the 3.3 & 4.7µm detectors, 7.8K for the 12 & 23µm detectors and 17K for the optical system, achieved using a two stage solid hydrogen cryostat. The scan mirror is driven in a sawtooth pattern to cancel the motion of the satellite for the 8.8s necessary to expose the arrays. This allows 1.1s for the flyback between exposures, for a total of 11s between exposures. In this way the instrument collect about 50GByte of data per day, which is transferred to the spacecraft mission unique board which provides a lossless 2.1:1 compression and stored on the 96GByte flash memory card for future downlink to the ground.

In order to preserve cryogen and to protect the sensitive WISE detectors and optics after the deployment of the cryostat aperture cover, pointing the aperture towards the Sun or Earth has to be avoided at all times. The WISE sunshield will be a cone cutoff at an angle with a normal vector $\vec{h}$, which will point $\theta = 8°$ from the Line of Sight: $\vec{h} = (0, -\sin\theta, \cos\theta)$. The unit vector towards the Sun, $\vec{S}$, will nominally point toward the +y axis, $\vec{S} \approx (0,1,0)$. The Sun avoidance requirement is that $\vec{h} \bullet \vec{S} < \sin(R_{Sun})$, where $R_{Sun} = 0.25°$ is the angular

radius of the Sun. A certain amount of thermal input into the cryostat by the Earth is unavoidable. The Earth avoidance constrains is therefore a compromise between maximizing the mission lifetime and its operability. The power input due to the Earth is negligible within $35°$ of the vector $(0, \sin 6°, -\cos 6°)$ and tolerable if the nadir is with $50°$ of the vector $(0, \sin 4°, -\cos 4°)$. As an adequate and achievable constraint the operations system enforces that the nadir will always fall within $40°$ of the vector $(0, \sin 5°, -\cos 5°)$.
A description of the pointing modeling software used as part of the Ground Data System that enforces these constraints, taking into account the performance of the WISE Pointing Control System, is described in *Ref. 11*.

3. MISSION OPERATIONS SYSTEM OVERVIEW

The WISE Mission Operations System is divided into three subsystems, summarized in Figure 3. The PI team at UCLA provides the scientific survey planning for the mission. On a weekly basis it generates the spacecraft pointings and scan parameters to execute an optimized survey plan allowing for SAA compensation, lunar avoidance and if necessary recovery of gaps resulting from inadvertent data losses, e.g. after a safe mode recovery. This leads to a nominal survey plan providing a coverage of better than 99.25% of the sky with more than 8 independent exposures during the 6 months prime mission.

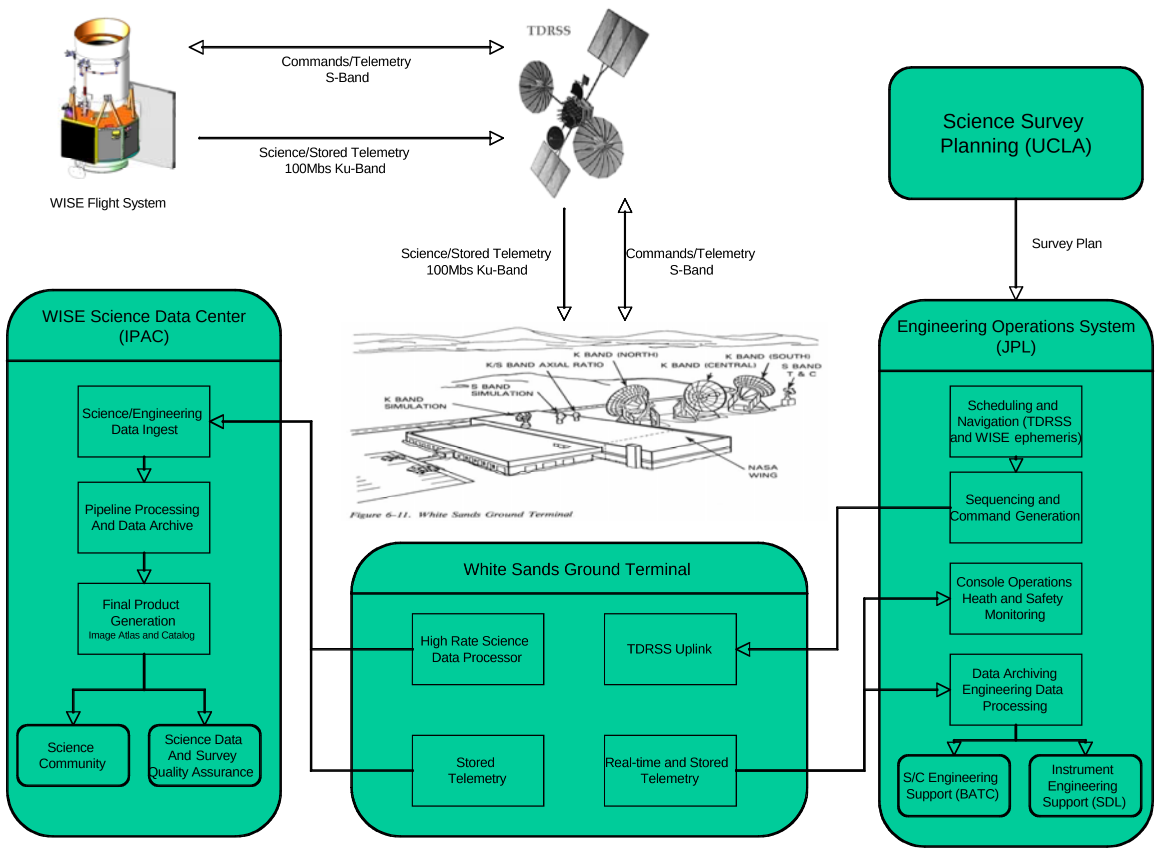

Figure 3 - WISE Ground System and Data Flow

Engineering operations for the mission are provided by the JPL Earth Science Mission Center, which is currently operating the Jason and Topex spacecrafts. The Engineering Operations (EOS) team of JPL engineers and operators supported by experts from both the spacecraft (BATC) and the science instrument (SDL) providers is forming an integrated spacecraft team during on-orbit operations. The EOS is responsible for the health and safety of all WISE mission operations. It will monitor the flight system and perform all necessary spacecraft and payload maintenance operations. It provides the detailed scheduling and navigation function and generates the weekly sequence loads to WISE via the TDRSS relay satellite system.

The goal of the WISE data concept is to provide a lasting legacy to the astronomical community in the form of a permanent whole sky source catalogue and image atlas in the mid-infrared (3.3 to 23µm). These products will be made accessible to the community in collaboration with the NASA Infrared Science Archive (IRSA) at the Infrared Processing and Analysis Center (IPAC), thus ensuring long-term availability of these products beyond the end WISE missions operations and data processing phase. As a baseline data will be made available to the community via the internet. The data will be maintained in a way that distribution of the complete WISE source catalogue via Digital Versatile Disk (DVD) to frequent users is possible. All image data will be made available in accordance with the Flexible Image Transport (FITS) astronomical data standard, tables will be in the widely used IPAC table format. In order to ensure survivability in case of a major catastrophe causing the loss of the data at the IPAC facility a complete copy of the WISE data set and software source code will be deposited at a secure off-site location.

A fundamental objective of the WISE project is to make data products available to the astronomical community as soon as is technically feasible and scientifically sensible. To facilitate this, WISE data products will be released in two stages. These will occur 6 and 17 months after the end of the nominal on-orbit lifetime of 7 months. The first data release will allow immediate use of WISE data by the community, and will consist of a preliminary image atlas and source catalog containing sources that have SNR of 20 or higher in unconfused regions of sky. The final data release will include sources to about SNR = 5 and will be accompanied by more extensive quality analysis and product validation.

4. OBSERVATION STRATEGY AND MISSION PLANNING

4.1. Survey Design

A simplified view of the planned WISE orbit is shown in Figure 4. This sun-synchronous polar orbit between 500-530km with a time of ascending node of 6pm will allow WISE to map the entire sky within 6 months as it travels with the Earth around the Sun.

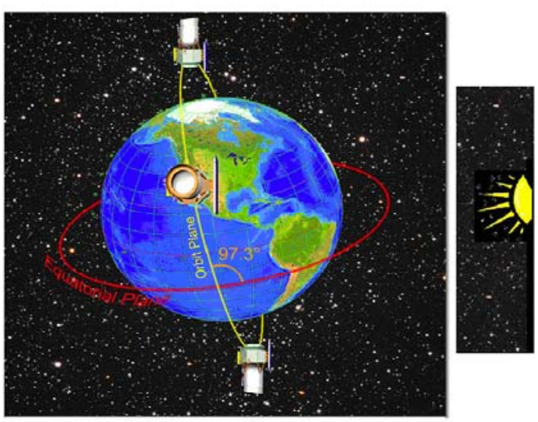

Figure 4 - The WISE Orbit

Given this orbit and the pointing constraints outlined above (Section 3.2) the simplest survey covering the whole sky design would scan the circle perpendicular to the spacecraft-Sun line with a scan rate equal to the orbital rate.

However this basic design will lead to gaps in the survey due to the Moon interfering when in it within 15° of the field of view due to its infrared stray-light interfering with the sensitive instrumentation. Due to the relative motion of the moon of 12° per day this would lead to gaps in the sky coverage about 30° high and 2.5° wide. In addition WISE will pass through the South Atlantic Anomaly (SAA) with its strong radiation environment impacting the data quality.

The modulation in the effective coverage due to the SAA can be improved by toggling the 47 arcmin WISE field of view back and forth every other orbit, so that each part of the sky is observed for a longer time than the modulation introduced by the 24 hour period of the particle hits due to the SAA passages.

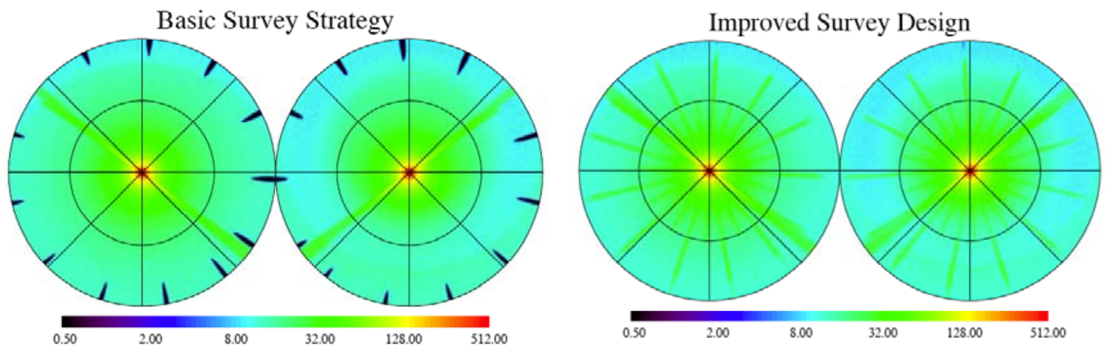

Figure 5 - WISE sky coverage with basic and improved survey design

The coverage gaps due to the moon can be avoided by moving the longitude of the central scan circle slightly faster than the Sun. This then allows twice per month to adjust the scan, effectively jumping back over the moon and observe the parts of the sky otherwise lost. Figure 5 shows the modeled sky coverage improvement utilizing this strategy. Figure 6 shows a depiction of the survey strategy with the longitude of the Sun in red, and the scan circle center in black, showing both the toggle and lunar avoidance (green intersection).

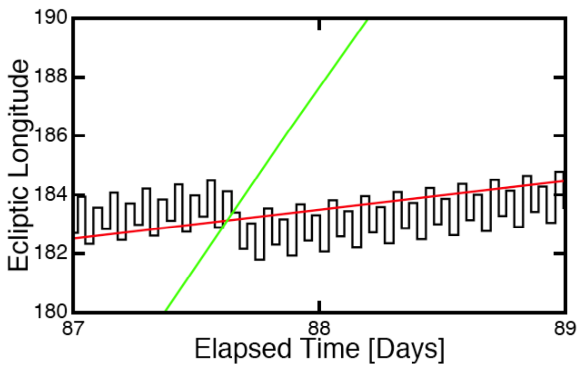

Figure 6 - WISE Survey Design

Given the avoidance geometry and the duration of the baseline mission of 6 months, portions of the sky will only be accessible once during the WISE mission, which poses a challenge relative to the goal of covering the entire sky. In order to be prepared for unexpected downtimes, like safeholds, which would open a gap in the sky coverage, the survey planning system allows biasing the scan circle a few degrees ahead of the Sun. This provides the opportunity to, rather than loose an area of the sky entirely, fall back and recover lost portions of the sky with a slightly decreased depths of coverage for downtimes of up to 5 days.

The WISE Principal Investigator team at UCLA develops the software, which implements this observing plan. During the mission it will be executed weekly (or in addition when a contingency requires an adjustment of the mission plan) to generate a set of spacecraft quaternions and rates that describe the exact orientations to be commanded for each half scan circle, which feed into the generation of the detailed operations sequence generated at the Engineering Operations Center (EOS) at JPL.

4.2. TDRSS Scheduling and Sequencing

The WISE spacecraft does not have a steerable high gain antenna, that means that the entire spacecraft has to be re-oriented to allow it to establish communication with one of the TDRSS relay satellites. This has to be done in such a way that the abovementioned pointing constrains are maintained and the scientific return of the mission is maximized by interfering as little as possible with the survey of the sky. The latter goal is achieved by only allowing downlinks to happen when WISE is above $45°$ ecliptic latitude, i.e. in areas of the sky where the orbit geometry provides a high level of redundant coverage. Extensive simulations have been performed using the Spacecraft Orbital Analysis Program (SOAP, Aerospace Corporation) to demonstrate that sufficient opportunities will be available during the WISE mission to perform the required 60min of high rate downlink per day without impeding on these limitations. The EOS will develop a software system that will generate time windows of possible TDRSS contacts and allow the scheduling of the TDRSS resources in these windows via the Space Network Web Services (SWSI). Once the TDRSS contacts have been confirmed the sequencing software will combine this schedule with the survey plan, by

	Monday	Tuesday	Wednesday	Thursday	Friday
-3 Wk				Receive/ Process OEF	Submit TDRSS Requests (Strawman)
-2 Wk	TDRSS Schedule Negotiations				
-1 Wk	Receive Conf. TDRSS Sched.	Process sequence inputs. Generate Sequence	Sequence Review/ Approval	Sequence upload	
0 Wk	Sequence Execution				

Figure 7 - WISE Scheduling and Execution Timeline

inserting the required detailed spacecraft maneuvers and tracks with the survey plan re-pointings into an integrated command sequence. At this stage of the planning process engineering maintenance activities are also introduced into the sequence of events. Most notably, there is the need to anneal the infrared detectors and to unload the reaction wheels using the on board torque rods. As both activities will degrade the quality of the science data they are either scheduled in conjunction with a downlink or during the time of a polar passages.

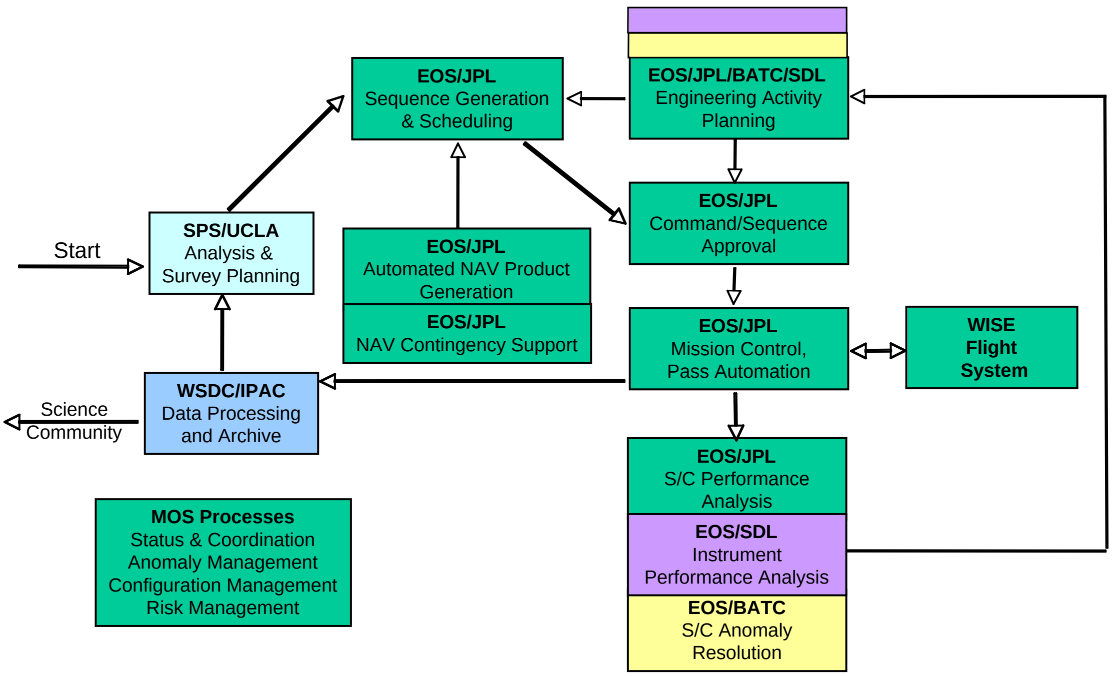

Figure 8 - WISE High Level Operations Flow

Prior to uplink a simulation will be performed on the final pointing sequence to ensure that the required maneuvers are within the performance envelope of the spacecraft and will not violate any of the pointing constraints either at the end points or in the course of a slew. As the WISE flight system does not have an Earth limb sensor in order for it to maintain its Earth avoidance ability in case of a Startracker failure the ground will update on-board ephemeris to match the ground simulation, with two line elements obtained from NORAD, about twice per week. All simulation logs are inspected and the generated uplink products undergo a final sequence approval process prior to uplink. This includes validation by the survey planning team for the correct implementation of the desired sky coverage.

Figure 7 shows the four week "rolling wave" timeline for the WISE planning and scheduling activities which implements the high level operations flow depicted in Figure 8. Typically there will be 3-4 TDRSS downlink passes and one S-band only path for health and safety check per day. These routine down-link passes are highly automated and could be executed without operator intervention, however, to allow fast response to anomalies all WISE communications will be under the supervision of a mission controller from the EOS.

5. ENGINEERING AND REAL-TIME OPERATIONS

The WISE real-time operations are performed using the WISE Telemetry Command and Communications Subsystem (WTCCS) an adaptation of a similar system used to support the Jason mission. It provides an integrated command and control system facilitating the communications with the White Sands Earth Terminal. It includes command translation, checking, transmission and logging, as well as de-commutation of the received real-time telemetry and an operator user interface allowing real-time monitoring and alarm checks. At the beginning of each TDRSS communication pass the EOS real-time operator will use WTCCS to establish the heath and safety status of the WISE flight-system by checking the status pages for any red or yellow alarm violations or unexpected flight-system configuration. In addition to this health and safety check, the housekeeping telemetry accumulated during each period of autonomy will undergo automated alarm checking and off-line analysis by the EOS spacecraft team to identify any possible transient anomalies or unexpected flight-system behavior.

The EOS also provides the first step in the processing of the high rate science data when it is received via TDRSS using a High Rate Data Processor located at the White Sands Ground terminal remotely operated from JPL by the EOS team. It will frame sync, RF decode and extract telemetry packets out of the high rate data stream, followed by packet level data accountability, which will be automatically evaluated based on pre-set thresholds for required data re-transmissions. Subsequently it will transfer the science packet data and extracted housekeeping data via data-lines to the WISE Science Data Center at IPAC for further processing.

6. SCIENCE DATA ANALYSIS AND ARCHIVING

The WISE Science Data Center (WSDC) as part of the Infrared Processing and Analysis Center at Caltech will implement the scientific processing system for WISE. There are two planned data release of a catalogue and image atlas for WISE at 6 and 17 months after the end of on-orbit operations (EoO). Covering 50% and 100% of the completed survey area respectively. The WISE mission will generate data at a high rate (~51GBytes of raw data per day) accumulating an overall data volume during the course of the mission of ~11TBytes raw and ~80TBytes processed. In order to meet this aggressive data release schedule and process this amount of data, while maintaining the highest scientific quality standards for reliability and completeness of the resulting catalogues, requires a highly automated pipeline system augmented by continuous tiered quality analysis. The resulting processing steps and timeline of the WISE science data processing flow are shown in Figure 9.

The Ingest system will autonomously receive and verify high-rate Level 0 science data from every downlink form the High Rate Processor in White Sands and write a raw data tape archive. At the same time it will copy ancillary telemetry received through the separate channel from WTCCS into the database and synchronize them to the raw frame image pool. It decompresses and assembles complete frames and integrates the meta-data into FITS-format images. As frames may be delivered out of order or spread out over several downlinks due to re-transmits, it will be necessary to stitch together images and orbits using the meta-data, QQC report and the directory of data in the frame pool.

In order to allow a fast recovery form any anomalies that can only be found in the scientific data from the instrument, rather than the housekeeping monitoring, e.g. a mis-synchronization of the scan mirror motion and the spacecraft scan speed or direction, a Quicklook Pipeline is run on each data delivery within 24 hours of receipt on about ~5% of the data. This will provide a quick assessment of the image quality and other basic quality parameters to allow if necessary the adjustment of the operational parameters with minimal loss of survey time.

When all data from a given orbit has been received completely or 72 hours has elapsed (since data can no longer be recovered from S/C after more than 3 days have past since the first transmission attempt) the Orbit Pipeline is executed. It calibrates all frames from a single orbit by deriving and applying flat fields, linearity correction and illumination profiles, and writes the resulting FITS frame into the image archive. For each band the orbit pipeline will also, extract and characterize high S/N sources, determine their positions through centroiding and comparison of the preliminary astrometric solution with the 2MASS Point Source Catalog. Finally the software will cross-compare and unify solutions for four bands by positionally associating the extractions from different bands, resolve and flag conflicts, produce a single multi-band extraction with refined position. In the process the pipeline collects various quality statistics (S/N, uncertainties, flags, etc.) for later analysis by the Quality Assurance Team.

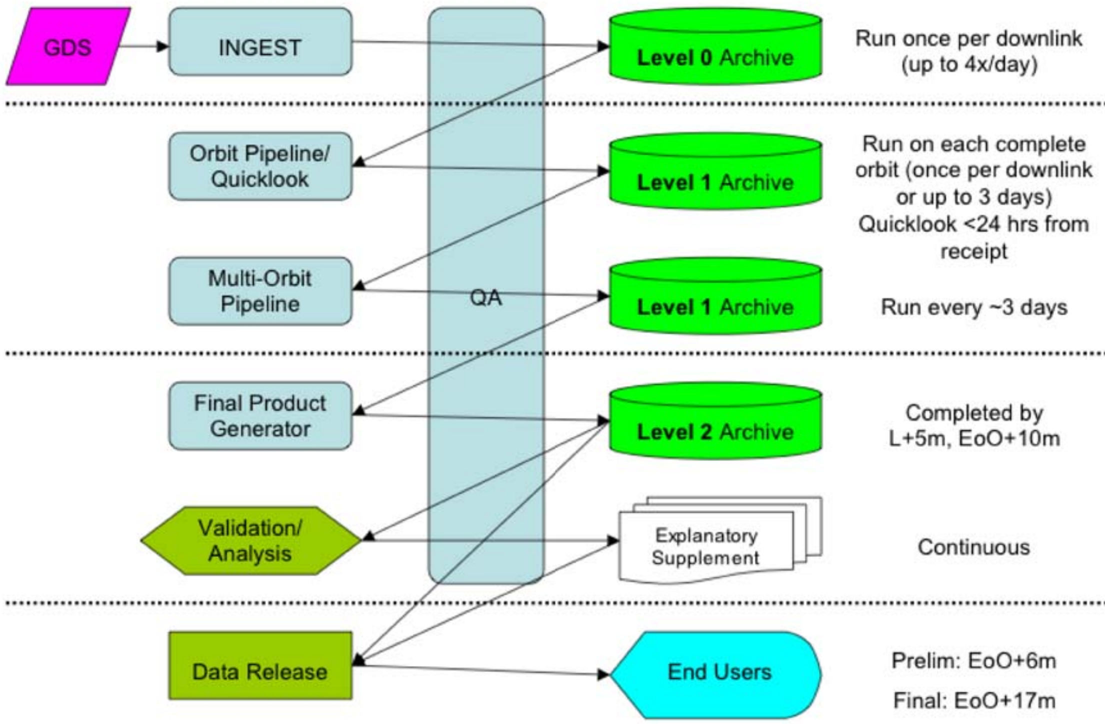

Figure 9 - Science Data Processing Flow

Once per week the Multi-orbit Pipeline is executed, which refines the processing by combining frame data from multiple orbits. The Multi-Orbit pipeline will function similar to the Orbit Pipeline, but will construct images, flag and coverage maps from combined multi-frame data, producing a "coadd" by reading overlapping calibrated frame images and flag maps and re-projecting and interpolating the frame data. It will also take into account the quality assessment from the Orbit Pipeline and reject data flagged as bad.

For each major delivery the Final Product Generator constructs the WISE Final Image Atlas and Source Catalog from the multi-orbit Image Archive and extracted source Working Databases. These final production runs are manually executed and continuously monitored by associated database queries of extraction and image meta-data.

At each stage of this multi-tiered processing, quality assurance is performed generating concise, web-based reports summarizing the science data quality. This is done for example by the examination of trend plots for individual images of sets of images, trending of point spread functions, astrometry and photometry of source extractions and analysis of extractable astronomical properties like logN vs. logs or color-color plots.

The final source database and image catalogue will be integrated into NASA/IPACs Infrared Science Archive (IRSA) allowing general community access though standardized astronomical query interfaces.

ACKNOWLEDGEMENTS

The work described in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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