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Key and Driving Requirements for the Juno Payload Suite of Instruments

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[Abstract] The Juno Mission was selected in the summer of 2005 via NASA's New Frontiers competitive AO process (refer to http://www.nasa.gov/home/hqnews/2005/jun/HQ_05138_New_Frontiers_2.html). The Juno project is led by a Principal Investigator based at Southwest Research Institute [SwRI] in San Antonio, Texas, with project management based at the Jet Propulsion Laboratory [JPL] in Pasadena, California, while the Spacecraft design and Flight System integration are under contract to Lockheed Martin Space Systems Company [LM-SSC] in Denver, Colorado. The payload suite consists of a large number of instruments covering a wide spectrum of experimentation. The science team includes a lead Co-Investigator for each one of the following experiments: A Magnetometer experiment (consisting of both a FluxGate Magnetometer (FGM) built at Goddard Space Flight Center [GSFC] and a Scalar Helium Magnetometer (SHM) built at JPL, a MicroWave Radiometer (MWR) also built at JPL, a Gravity Science experiment (GS) implemented via the telecom subsystem, two complementary particle instruments (Jovian Auroral Distribution Experiment, JADE developed by SwRI and Juno Energetic-particle Detector Instrument, JEDI from the Applied Physics Lab [APL]--JEDI and JADE both measure electrons and ions), an Ultraviolet Spectrometer (UVS) also developed at SwRI, and a radio and plasma (Waves) experiment (from the University of Iowa). In addition, a visible camera (JunoCam) is included in the payload to facilitate education and public outreach (designed & fabricated by Malin Space Science Systems [MSSS]).

This paper describes the instruments, the mission objectives, the payload's key and driving requirements, and expected development challenges.

I. Introduction

THE Juno Mission was selected through NASA's competitive AO process. Juno is the second New Frontiers mission. Information from NASA HQ is available via http://newfrontiers.nasa.gov/missions_juno.htm. The New Frontiers program office is located at MSFC, so information is also accessible from http://discoverynewfrontiers.msfc.nasa.gov. The main public site for the Juno project is http://juno.wisc.edu/.

Juno's goal is to understand the origin and evolution of Jupiter. As the archetype of giant planets, Juno's investigation focuses on four themes: Origin, Interior Structure, Atmospheric Composition and Dynamics, and the Polar Magnetosphere. Information in Sections I and II of this paper was taken from Bolton, et. al. [TBC: 2007][1]

The Juno mission [2, 3] will be implemented as a Risk Classification B payload as defined by NPR 8705.4, "Risk Classification for NASA Payloads". Characteristics of class B include critical SPFs for level 1 requirements minimized and mitigated, full safety program, NASA Parts Selection Level 2, formal review program, reliability

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analyses, quality assurance, software assurance, and risk management. These and JPL-institutional requirements are flowed-down through Juno project documentation.

The Juno mission is a cost-capped mission with the final cost, including launch vehicle and reserves, negotiated at the time of mission confirmation (at the time of the AO, the cost cap was $700M in FY03 dollars). The Payload System budget (phases B through D) is expected to be approximately 10% of the total Juno cost cap. It includes the cost of payload system management, payload system engineering, and the instruments.

Each instrument will be built to its own institutional standards and processes. The Juno payload team is working to understand these processes and ensure they meet the intent of flowed-down NASA, JPL-institutional and Juno project requirements. Where they don't, processes will be augmented or waivers will be written as appropriate.

Management of the Juno Payload

The Juno Payload is so diverse that a dedicated Payload System Office was established (see Figure 1) to help manage and oversee the complicated instrument developments and their interfaces to the Spacecraft. In addition to having a reporting path to project management via the Payload Office, each instrument's lead Co-Investigator has another reporting path straight to the Principal Investigator (as part of the Science Team) The Juno Payload is the collection of instruments that are supported by the spacecraft to carry out the Juno science mission. In other words, it is the equipment provided for science purposes in addition to the normal equipment integral to the spacecraft. It includes experimental and scientific data gathering equipment placed on board the Flight System (ref. NASA definition in 7120.5D = NASA Space Flight Program and Project Management Requirements). In the case of the Juno Project, a minor adaptation is employed. The equipment for the Gravity Science investigation is so tightly coupled with the S/C telecomm subsystem that the resources for it are not handled by the Payload System Office. In Figure 1, the JIRAM instrument is a recently-negotiated (while this paper was in development) international contribution[4] from the Italian Space Agency (ASI), and will not be covered in this paper to the same level of detail as the other instruments. A simple definition is that the payload is what produces the science data, and customarily the volume of science data far exceeds the volume of engineering data.

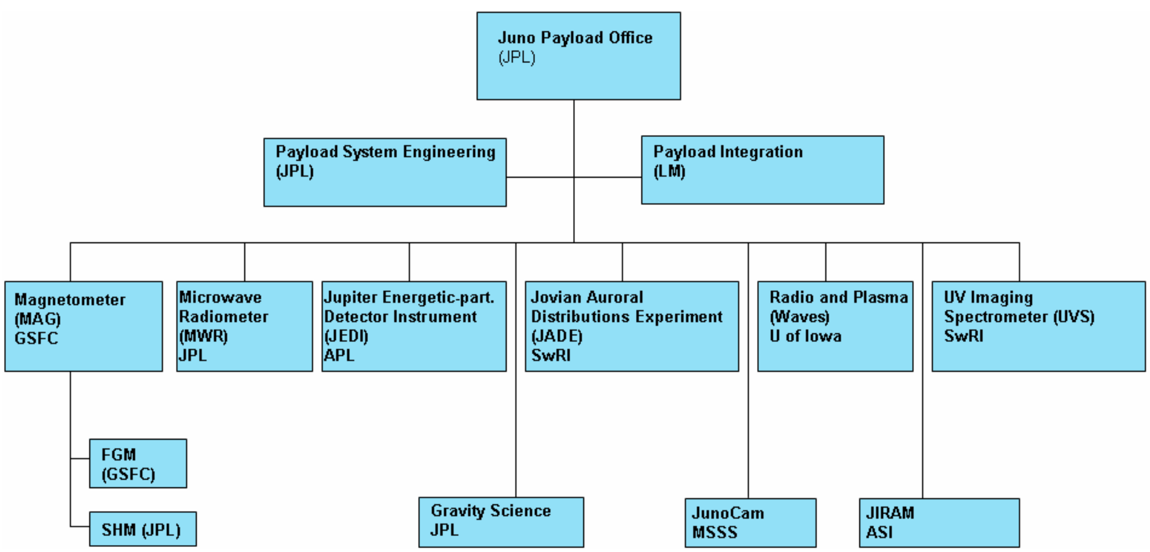

Figure 1, Juno Payload team organization

II. Juno Mission & Science Objectives

The Juno Project will place a solar-powered, spinning Flight System into an elliptical orbit around Jupiter. Nominally, the Flight System will be in a polar orbit around Jupiter for about one Earth-year. Launch is planned to take place from Cape Canaveral Air Force Station on a medium or heavy class launch vehicle. Launch is presently planned for a window opening in August 2011. To maximize the payload delivery to Jupiter, a Delta-Velocity Earth Gravity Assist (ΔV-EGA) trajectory is utilized. A Deep Space Maneuver (DSM) is planned for ~11 months after launch to adjust the trajectory for an Earth Fly-By (EFB) about 15 months after the DSM. After an additional 36 months of interplanetary cruise, the Flight System arrives at Jupiter where a Jupiter Orbit Insertion (JOI) burn places the Flight System into an interim 77-day capture orbit. A Period Reduction Maneuver (PRM) establishes the ~11-day science orbit around Jupiter, and the prime mission is defined with 32 orbits which allows the entire mission to be completed between solar conjunctions. Major events leading to JOI are shown in Figure 2. The orbit period was chosen by the science team to establish equatorial crossings with equal latitude spacing, as shown in Figure 3. The orbit also places the spacecraft in sunlight, thus maximizing power production and thermal stability at Jupiter. Primary science data is collected during the six hours around each Peri-Jove (PJ) pass. The orbital tour is simplified to have only two orbit types: radiometer passes and gravity passes (referred to as MWR orbits and Gravity orbits, respectively, in Table 3). The elliptical polar orbit with close Peri-Jove [1.06 R_J] allows the Flight System to avoid the bulk of the Jovian radiation field, as indicated in Figure 4 (which shows orbits 2, 17, and 32). Jupiter impact (after one year of orbiting) is nominally planned on 10/16/2017 (for planetary protection considerations).

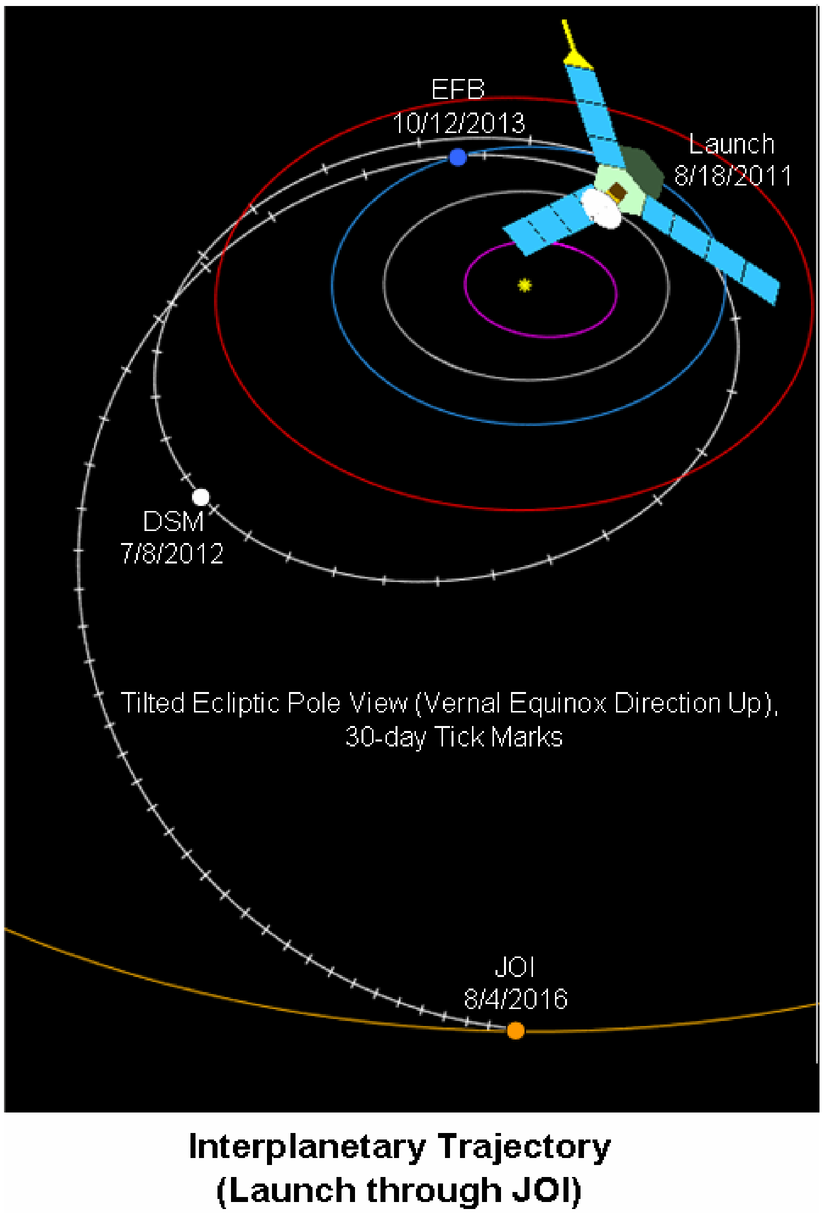

Figure 2

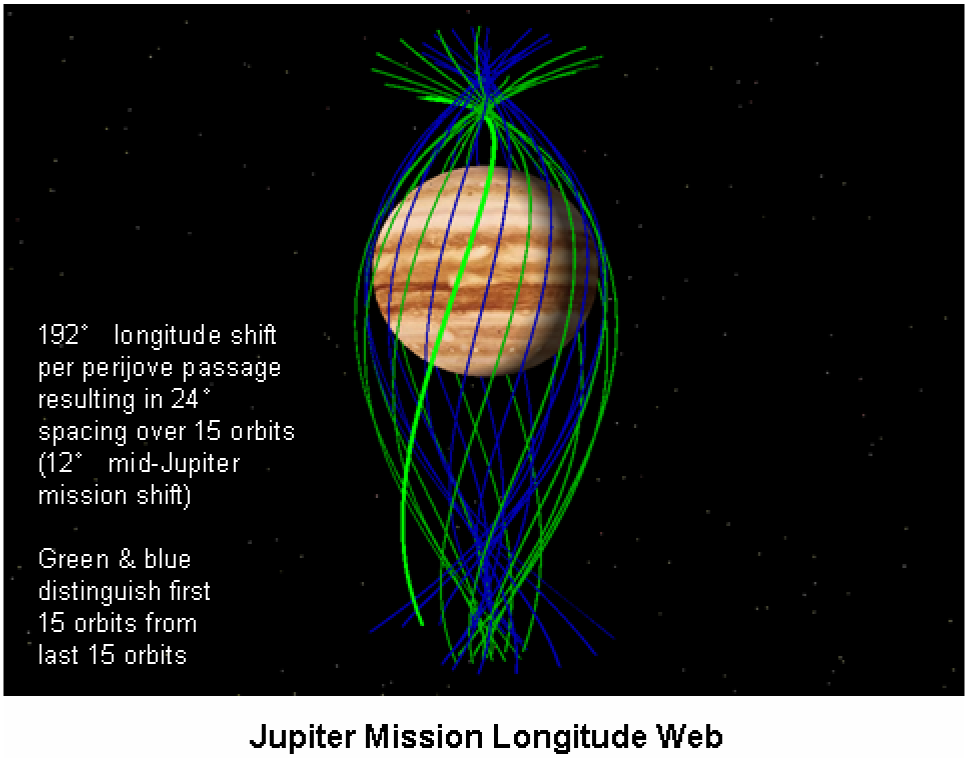

Figure 3

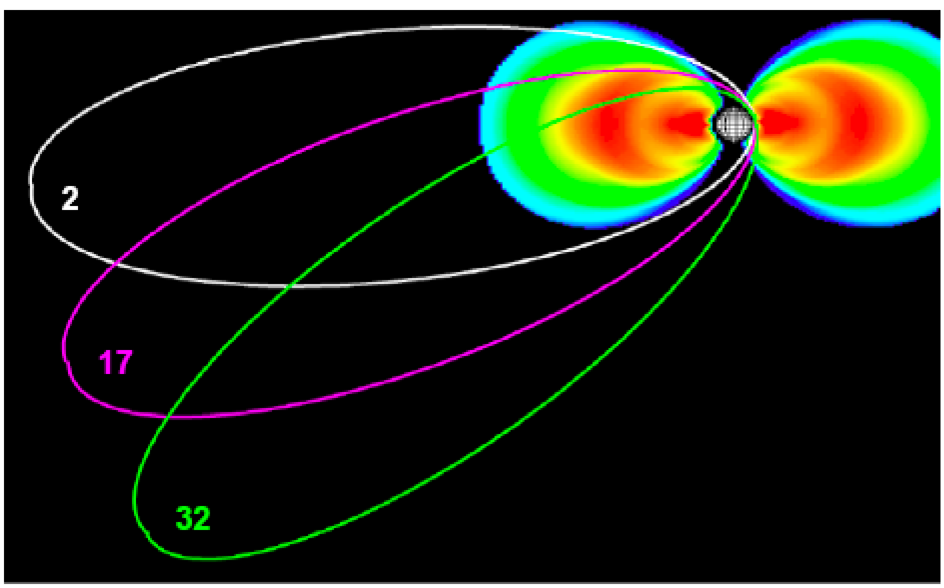

Figure 4, Avoiding Jupiter's radiation

III. Spacecraft & Payload Description

Together, the Spacecraft and Payload make the Flight System. The Spacecraft is designed and manufactured by Lockheed Martin Space System Company (LM-SSC) in Denver, Colorado. LM is also the Flight System integrator.

A summary of the important characteristics of each instrument is shown in Table 1.

Science Instrument Capabilities			
Instrument	**Science Theme/Requirement**	**Attributes**	**Payload Requirements**
Gravity Science	**Interior Structure:** Determine the high-order gravity coefficients	X-Band RF Frequency	7.153 GHz - 8.404 GHz
		Ka-Band RF Frequency	32.083 GHz - 34.365 GHz
MAG	**Interior Structure & Magnetic Dynamo:** Measure vector magnetic field with high accuracy over a large dynamic range	**SHM** - Range	0.1 G - 12 G
		SHM - Accuracy (perijove pass)	0.002%
		FGM - Range	0.2 nT - 12 G
		FGM - Accuracy	0.05% or 0.5 nT
		ASC - Attitude Det	1 mrad
MWR	**Deep Atmospheric Sounding & Composition:** Measure the microwave brightness temps of Jupiter with high precision	Radiometer Frequency	600 MHz, 1.2 GHz, 2.4 GHz, 4.8 GHz, 9.6 GHz, 22 GHz
		Beamwidth	<22°
		Relative Precision	0.1%, 1-sigma
JEDI	**Auroral Distributions, Ion Composition:** Measure pitch angle and energy distributions of electrons and ions over both Jovigraphic polar regions.	Electron Energy Range	40 keV - 500 keV
		Ion Energy Range	20 keV - 1000 keV
		E&I Energy Resolution	25%
		Mass Resolution	H, He, O/S
		FOV (per head)	160° x 12° (x3 heads)
JADE	**Auroral Distributions, Ion composition:** Measure pitch angle and energy distributions of electrons and ions over both Jovigraphic polar regions.	**JADE-E** Energy Range	200 eV - 40 keV
		JADE-E Energy Resolution	50% (200 eV - 5 keV) 15% (5 keV - 40 keV)
		JADE-E FOV	120° x 60° (x3 sensors)
		JADE-I Energy Range	<13 eV - >20 keV
		JADE-I FOV	>1.5 pi sr
		JADE-I Mass Range	1 - 32 AMU
Waves	**Radio & Plasma Waves:** Measure radio and plasma wave emissions associated with auroral phenomena in the polar magnetosphere.	E Frequency Range	50 Hz - 40 MHz
		Max measurable E-Field Intensity	3 V/m
		B Frequency Range	50 Hz - 20 kHz
		E/B Temporal Resolution	1 spectrum/sec
UVS	**Spatial, Spectral & Temporal Auroral Structure:** Characterize the UV auroral emissions.	Spectrum	78 nm - 172 nm
		Spectral Resolution	<3 nm
		Spatial Resolution	<500 km
JIRAM	**Auroral Structure, Troposhere Structure, Atmospheric sounding:** Acquire infrared images and spectra of Jupiter.	IR Range	2 µm - 5µm
		Spectral Resolution	10 nm
		FOV	3.5° x 6.24°
JunoCam	**E/PO:** Provide first pictures of Jupiter's poles.	Resolution	<50 km/pixel
		SNR	>75
		IFOV	0.61 mradians/pixel
		Spectral Range	400 nm - 900 nm (3 colors)

Table 1, Key & Driving Requirements of the Juno Payload Instruments

A. Overview: Ten investigations compose the Payload

The coverage of the electromagnetic (EM) spectrum of the Juno payload is shown in Figure 5. Note that the envelope of the six MWR frequencies is shown in this figure.

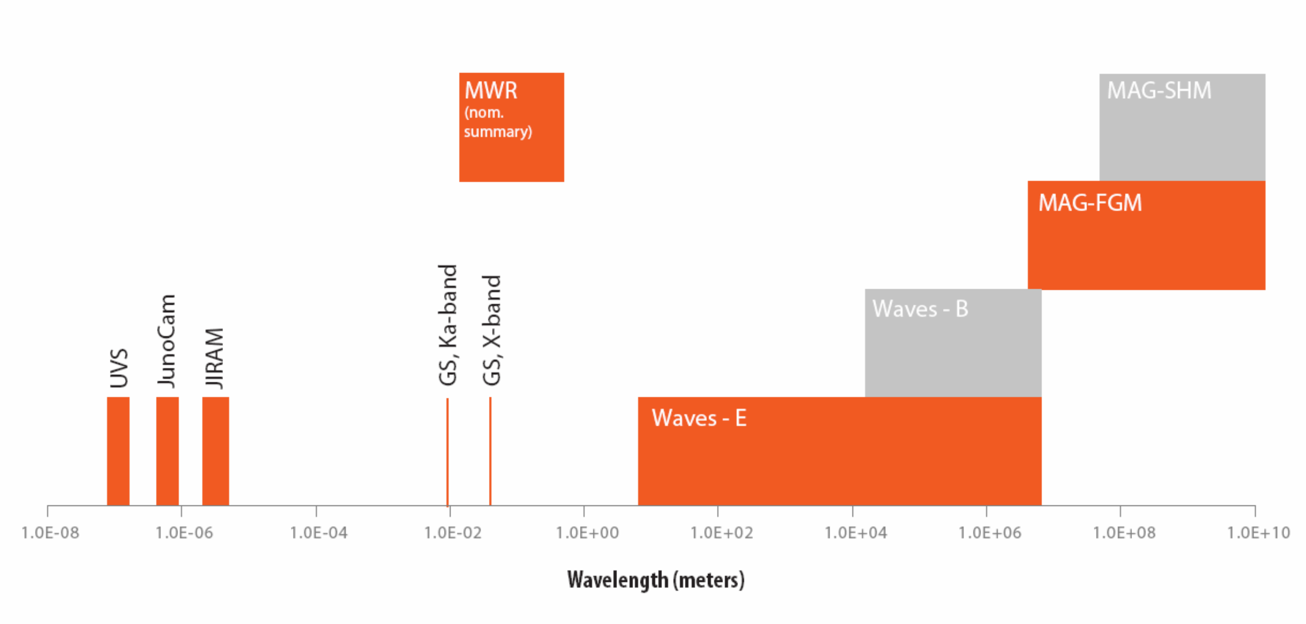

Figure 5, Payload Electromagnetic Spectrum Coverage

In addition to covering the EM spectrum, a range of particle energies (both electrons & ions) is covered as shown in Figure 6.

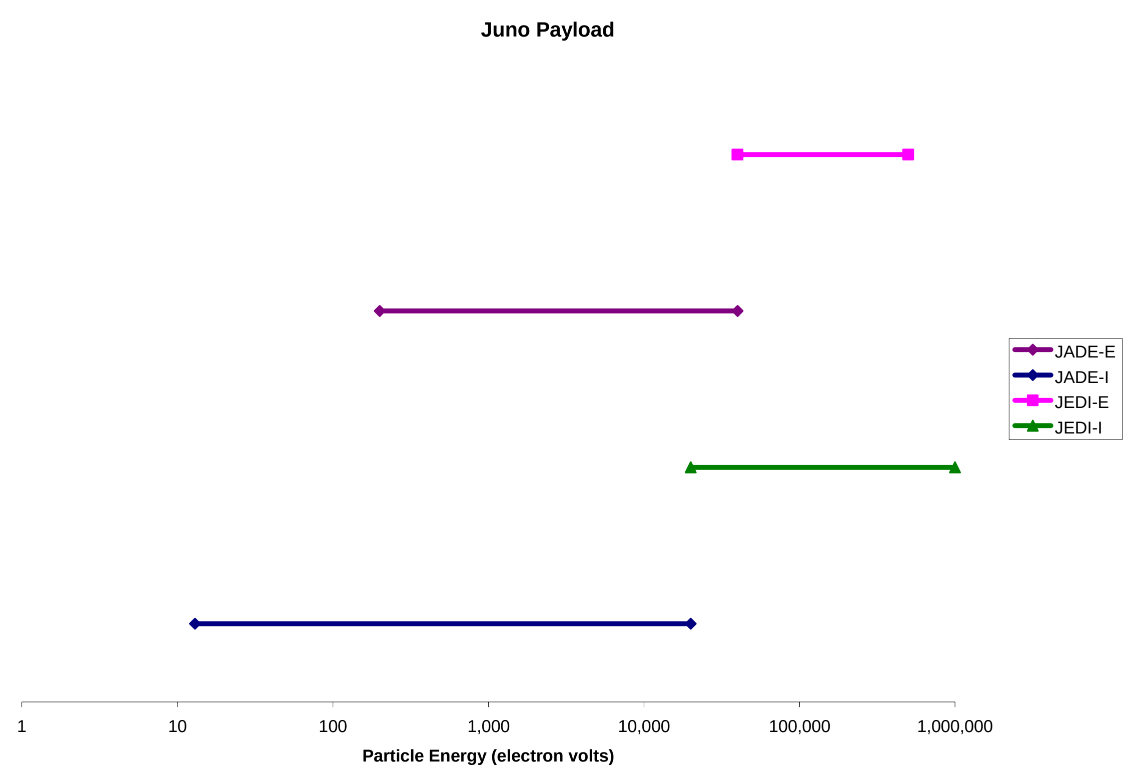

Figure 6, Juno Coverage of Particle Energies

As of this time (pre-PDR), key resource allocations for the instruments are shown in the following tables.

1. *Mass*

Subsystem/Component	Total Flt Allocation
PAYLOAD	**173.7**
Jupiter Energetic-particle Detector Instrument (JEDI)	21.60
FluxGate Magnetometer (FGM) [includes ASC]	15.25
Scalar Helium Magnetometer (SHM)	9.08
Radio & Plasma Wave Instrument (Waves)	10.87
Jovian Auroral Distribution Experiment (JADE)	27.52
Microwave Radiometer (MWR)	42.13
Ultraviolet Spectrograph (UVS)	13.65
JunoCam	1.66
JIRAM	13.10

Table 2: Juno Mass Allocations, kg

Gravity Science mass is book kept as part of the telecomm subsystem.

2. *Power*

Power allocations	MWR orbits, orb-cruise	MWR orbits, PJ	Gravity orbits, orb-cruise	Gravity orbits, PJ
Science Instruments	W	W	W	W
JEDI	9.7	9.7	9.7	9.7
FGM (incl. ASC)	11.3	12.5	11.3	12.5
SHM	6.5	6.5	6.5	6.5
Waves	5.2	9.6	5.2	9.6
JADE	9.0	17.3	9.0	17.3
MWR	32.6	32.6	0.0	0.0
UVS	TBD	11.8	0.0	11.8
JunoCam	0.0	6.0	0.0	6.0
JIRAM	TBD	18.4	0.0	0.0

Table 3, Juno Power Allocations

Gravity Science power is book kept as part of the telecomm subsystem. The UVS and JIRAM MWR orbit cruise allocations will be finalized once calibrations needed during this period have been defined.

3. Data Volume

The Juno Project downlink data volume allocation (Base-10) for each Juno MWR science orbit is presently as follows:

JEDI Data	280 Mbits
FGM Data	380 Mbits
ASC Data	360 Mbits
SHM Data	40 Mbits
Waves Data	410 Mbits
JADE Data	330 Mbits
MWR Data	100 Mbits
UVS Data	500 Mbits
JunoCam Data	320 Mbits
JIRAM Data	100 Mbits

Data Volume margin is held at the Project-level.

Gravity Science does not produce 'data' on-board the Flight System (it is all generated at the ground station), so no allocation is applied. Also note that framing overhead is excluded from the above numbers.

B. Individual Instruments

1. Magnetometer (MAG)

The MAG experiment contains a fluxgate magnetometer developed by GSFC, a scalar helium magnetometer developed by JPL and magnetically clean star cameras (Advanced Stellar Compass, ASC) developed by Danish Technical University (DTU). All sensors are mounted on a stable magnetometer boom located at the end of one of the solar array wings. An inboard and outboard magnetic field measurement provides the capability to subtract the contribution from the spacecraft magnetic field. The MAG electronics are contained in the radiation vault of the Flight System.

Driving requirements for the MAG include the range of magnetic field magnitude sampled, electromagnetic cleanliness requirements (EMC), star camera pointing precision, and optical bench stiffness.

2. Microwave Radiometer (MWR)

MWR contains six antennas and receivers to obtain measurements at six frequencies: 600 MHz, 1.2 GHz, 2.4 GHz, 4.8 GHz, 9.6 GHz and 22 GHz. All components, except the antennas and associated feed lines, are located in the radiation vault. The MWR sounds the deep atmosphere of Jupiter (where the pressure is greater than 100 bars) to investigate the dynamics and structure of Jupiter's atmosphere below the visible cloud top layer. A prime objective of the MWR is to determine the global water abundance in Jupiter, a measurement which requires a precise instrument. The MWR electronics box and radiometer box are housed in the radiation vault.

Driving requirements for the MWR include measurement precision (relative as opposed to absolute), antenna beam patterns, frequency range, EMC, and radiation tolerance.

3. Gravity Science

The Gravity Science investigation uses both flight and ground elements. The basic measurement is the Doppler shift in the tracking frequency measured by the ground station during the Jupiter perijove periods. The flight elements consist of both X-band and Ka-band translators (KaT) and power amplifiers. The ground element consists of a Ka-band transmitter and receiver supplementing the X-band system. The ground elements also include an advanced water vapor radiometer to determine the water vapor in the Earth's troposphere. The combination of the X- and Ka-system makes the investigation less susceptible to dispersive noise from plasma in the solar wind and the Earth's ionosphere.

Driving requirements for the gravity science include frequency bandwidth, dual band up/down capability and system noise levels.

4. Jupiter Energetic-particle Detector Instrument (JEDI)

JEDI measures energetic electrons and ions to investigate the polar magnetosphere and the Jovian aurorae. Ions are measured, and discriminated by elemental composition, using a Time-of-Flight (TOF) versus energy (E) technique. Each JEDI sensor has six ion and six electron views arrayed into 12 x 160 degree fans. Two JEDI sensor units are configured to view into a ~360 degree fan normal to the spacecraft spin axis to obtain complete pitch angle snapshots at every instance when the spacecraft is close to Jupiter. A third JEDI sensor unit views in a direction aligned with the spacecraft spin axis, and obtains all-sky views over one complete spin period (~30 seconds). Each JEDI sensor is self-contained, so there is no JEDI hardware included in the radiation vault.

Driving requriements for the JEDI experiment include measurement environment dynamic range, penetrating radiation, angular coverage combined with resolution, energy, launch environment, and radiation tolerance.

5. Jovian Auroral Distribution Experiment (JADE)

JADE measures low energy electrons and ions to investigate the polar magnetosphere and the Jovian aurora. JADE measurements include the pitch angle distribution of electrons, ion composition and the three-dimensional velocity-space distribution of ions. JADE comprises a single head ion mass spectrometer, three identical electron energy per charge (E/q) analyzers and three Faraday cups to measure the full auroral ion and electron particle distributions. The JADE electronics (LVPS, DPU, and HVPSs), other than pre-amplifiers, are provided in a dedicated box that is located inside the radiation vault.

Driving requirements for the JADE experiment include energy, mass and angular resolution, pointing knowledge, low energy cutoff, EMC, launch environment, and radiation tolerance.

6. Ultraviolet Spectrograph (UVS)

The UVS instrument images and measures the spectrum of the Jovian aurora in the 78-172 nm range of the electromagnetic spectrum. The spectral images are used to characterize the morphology and investigate the source of Jupiter's auroral emissions. Juno UVS consists of two separate components: a dedicated optical assembly and an electronics box. The UVS electronics box is located in the Juno radiation vault.

Driving requirements for the UVS experiment include wavelength range, single-photon sensitivity, launch environment, and radiation tolerance.

7. Radio and Plasma Waves (Waves)

Waves measures both the electric and magnetic fields components of in-situ plasma waves and freely propagating radio waves associated with phenomena in Jupiter's polar magnetosphere. The instrument includes two sensors: a dipole antenna for electric fields and a magnetic search coil for the magnetic component. The instrument has two modes to scan over relevant frequencies and a burst mode to capture waveforms. Waves' electronics (including low- and high-frequency receivers) are located in the radiation vault.

Driving requirements for the Waves experiment include frequency coverage, launch environment, and radiation tolerance.

8. Visible-spectrum Camera (JunoCam)

The JunoCam camera provides full color images of the Jovian atmosphere at resolutions as good as 25 km per pixel to support Education and Public Outreach (E/PO). JunoCam consists of two parts (both mounted outside of the radiation vault), the camera head, which includes the optics, detector, and front-end detector electronics, and the electronics box, which includes the FPGA, the image data buffer and DC-DC converter. It acquires images by utilizing the spin of the spacecraft in "push-broom" style. The JunoCam hardware is based on the Mars Descent Imager (MARDI) currently under development for the Mars Science Laboratory. JunoCam is designed to obtain high resolution full disk images of both pole regions of Jupiter.

JunoCam does not carry science requirements as it is included in the payload to facilitate public outreach. JunoCam does have to meet requirements associated with specific radiation tolerance (although they are relaxed relative to the other instruments), field of view, and color filters.

9. Juno Infra-Red Auroral Mapper (JIRAM)

JIRAM is an infra-red imager and spectrometer. JIRAM obtains high spatial resolution images of Jupiter and investigates the atmospheric spectrum in the 2.0-5.0 µm range. The measurements contribute to the investigation of both the polar aurora and atmospheric dynamics through complementary observations with MWR and the magnetospheric suite of experiments (JADE, JEDI, UVS and MAG). The JIRAM optical head and electronics are accommodated outside of the radiation vault.

JIRAM was added to the Juno payload after mission selection, and thus is not required to satisfy the highest-level (NASA level 1) requirements. JIRAM does have to meet requirements associated with specific radiation tolerance (reduced, like JunoCam), field of view, and spectral capability.

The majority of instrument sensors and their orientation on the spacecraft are shown in Figure 7.

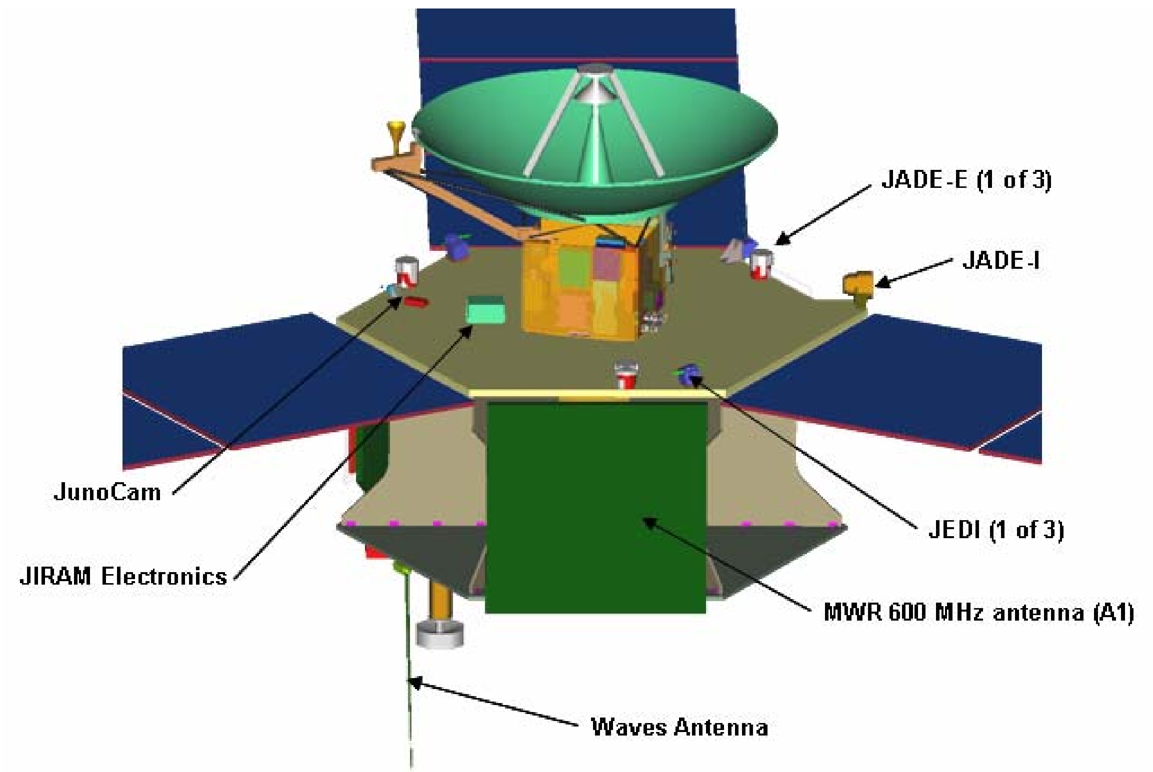

Figure 7, Juno Flight System Configuration (non-Payload components omitted for clarity)

Figure 8 shows another view of the Flight System, indicating most of the MWR Antennas (where the antennas for each of the six signal chains are labeled A1 to A6, increasing in frequency), and the Waves electric antenna (in light green) in its deployed configuration.

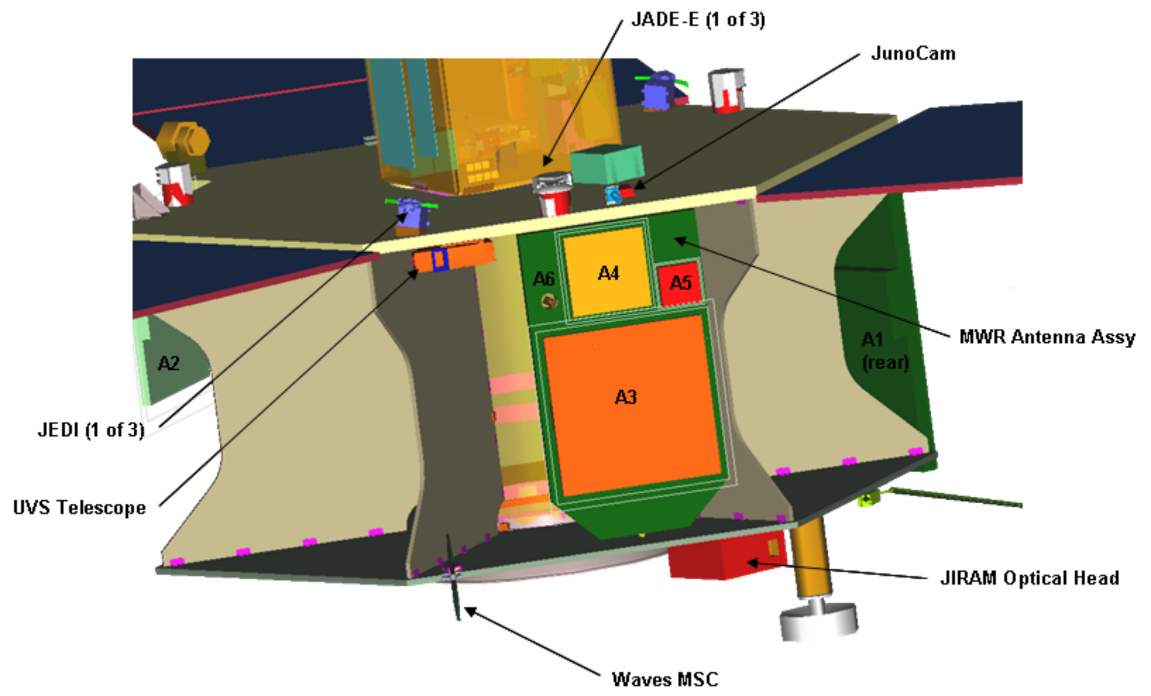

Figure 8, More Juno Flight System Sensors

C. Major Architectural Features of the S/C

The Juno Flight System, as shown in Figure 9, is spin-stabilized about the major principal axis, with a large spin-to-transverse moment of inertia ratio under all flight conditions. Powered by three large deployable rigid-panel solar array wings, the vehicle includes cross-strapped avionics, a RAD750-based command and data handling system, and ample resources to accommodate this large payload. The spacecraft uses proven hardware and software from past missions such as MGS, Stardust, Odyssey, Genesis, and MRO.

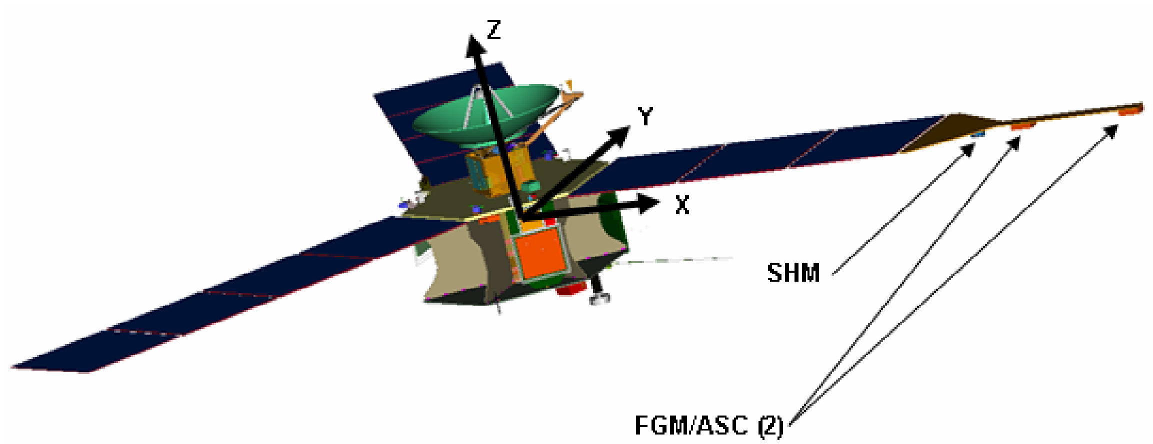

Figure 9, Juno axes

The Juno primary structure consists of a main and aft deck, stiffened with a central torque tube and panels, and a launch adapter. It is made of composite material with some metallic details. Most radiation-sensitive components are located inside the electronics vault, which is designed as a radiation shield. High-heat-dissipating components are mounted on the vault sidewalls and a combination of louvers and fixed area radiators are used to reject the heat to space. A unique piece of the structure is the mag-boom which holds the SHM & FGM sensors as shown in Figure 10.

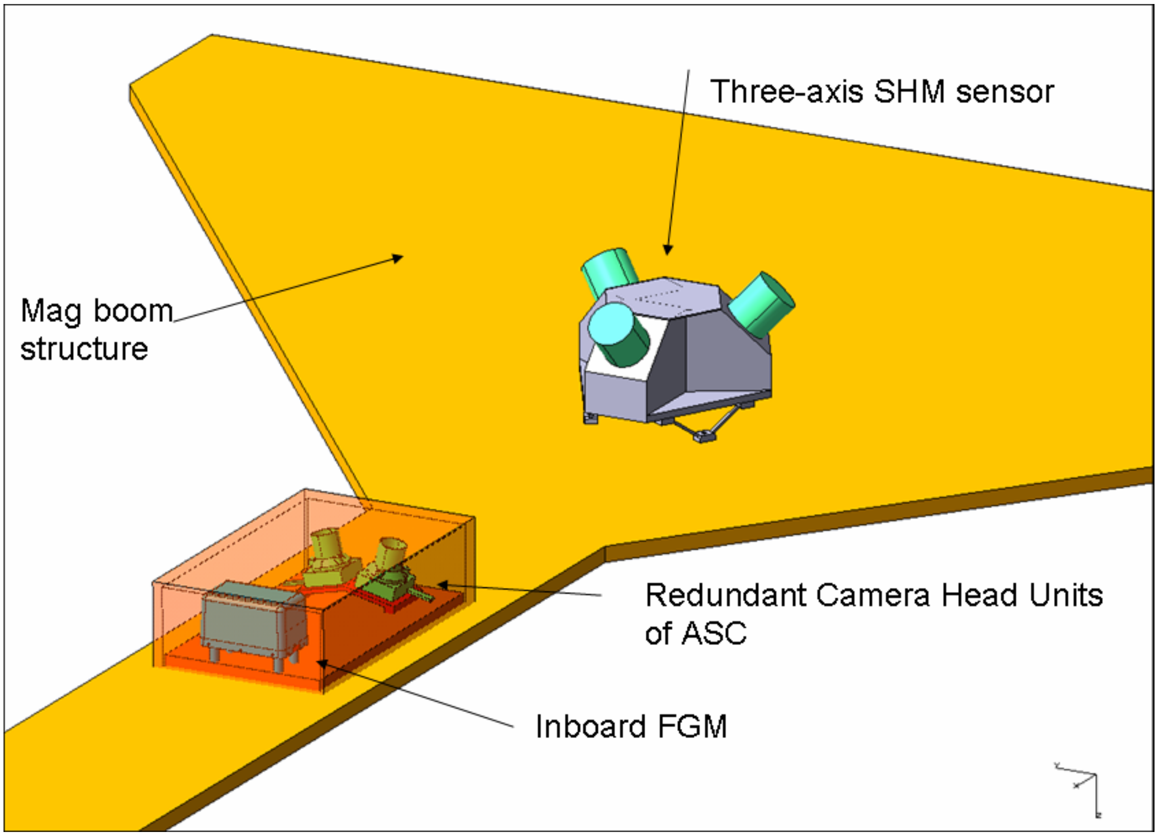

Figure 10, Mag boom components

There are minimal mechanisms on the spacecraft, consisting of only those associated with the solar arrays and a main engine cover.

Juno's dual-mode propulsion subsystem operates in biprop mode (N_2O_4/Hydrazine for the major delta-V burns, and in monoprop mode (blow-down hydrazine) for spin-up/down, precession, and trajectory correction maneuvers. Twelve 22-N RCS thrusters are presently baselined.

While in Jupiter orbit, the nominal spacecraft spin rate is 2 rpm. Active attitude control is not required during the science perijove pass (minimizes disturbances to the science investigations), where the radiation flux is high, and accurate attitude knowledge can be maintained with infrequent star observations. Two stellar reference units, two inertial measurement units, and two spinning sun sensors provide block redundant information for attitude and spin rate determination.

Except for minimal off-sun maneuvers, the Juno mission is accomplished in sunlight, thus maximizing power production and thermal stability at Jupiter. The solar arrays contain over 30 m^2 of solar cells and the strings are individually compensated to null their magnetic moments. Two Li-ion batteries provide power during off-sun maneuvers.

The telecommunications subsystem provides X-band command uplink and X-band science and engineering telemetry data downlink throughout the entire post-launch, cruise, and orbital phases of the mission at Earth ranges up to 6.4 AU. It also provides the two-way Ka-band link for gravity science. The telecomm suite of antennas includes a HGA, LGAs, and a toroidal antenna on the aft deck.

The Flight System accommodation of the payload includes requirements for mass, power, volume, field of view, operation, thermal control, attitude control/pointing, command and data handling, magnetic and EMC/EMI cleanliness, contamination control, radiation shielding, and instrument/spacecraft calibrations. Standardized RS-422 interfaces are employed, including a low speed asynchronous interface and a high speed synchronous interface.

The payload software is separated from the spacecraft bus software to eliminate the risk of payload software corrupting spacecraft software. It is separately loadable and up-linkable; providing flexibility of delivery and integration scheduling during ATLO and flight operations. The payload software domain consists of simple modules to manage the command, telemetry, and fault protection functions.

IV. Key and Driving Requirements

A. The Juno Payload System Requirements Process

The key and driving requirements of the Juno Payload have been developed cooperatively among all the parties shown in Figure 1. The process has been iterative and responsive to higher-level requirements developed in Phases A and B of the Juno project. Several critical Payload technical interface meetings have been conducted over more than a year's time to generate the requirements, and then clearly determine which are key and driving. Additional technical meetings are expected in the near-term to complete the requirements generation process for the Juno payload system.

The Juno Payload System requirements are managed using the DOORS requirements database. Requirements at levels both above and below the Payload System were also planned in the same database providing an easy method of linking requirements from one level to another. Attributes are defined for each requirement including the requirement text, rationale, owner, and verification method. This allows end-to-end management of the entire requirements definition, verification and validation process. Requirements at levels above the Payload System are presently under configuration control in DOORS. Payload System requirements will go under configuration control with their next release.

B. Definition of" Key and Driving" Requirements

1. Key Requirements

Key requirements are allocated by an upper-level element for items that are considered critical. Critical items can pertain to public safety, planetary protection and they are usually related to science goals or mission-critical parameters. Key requirements are essential to identify in order to build a robust system.

2. Driving Requirements

Driving requirements are identified by a lower level element as impacting the design or implementation of that element in a major way. Driving requirements are usually associated with performance, cost, mass, and schedule. In addition, driving requirements effectively define the architecture of the System or element(s). They involve the type of technology, type of equipment required, number of units, or software functionality

C. A Sampling of Key and Driving requirements from the Juno Payload

The random vibration environment.

The random vibration environment (as defined by the spacecraft based on the launch vehicle acoustic input) is higher than the instruments' heritage environments, so special efforts are underway to address those differences. For radiation protection reasons, the Flight System incorporates a radiation vault in its core that houses the majority of the Flight System electronics. This vault concentrates the electronics mass in a small area so that the edges of the Flight System's forward and aft decks are lightly loaded. The random vibration environment for these areas is currently higher than the heritage qualification envelope for several of the instruments (notably JEDI, JADE and UVS).

Three paths are being pursued to address this issue. The S/C team is investigating methods to reduce levels by modifying the S/C design. This includes evaluation of options to reduce the random vibration environment through redesign of the structure and options to lower the environment seen by the instruments by reducing the response of structure. Instrument teams are assessing design modifications to improve robustness (tasks like better support for MCP mountings, or additional mounting points at the S/C interface). In addition, relief from the launch vehicle's acoustic specifications is under investigation.

Maintain heritage while dealing with the Jupiter environment.

Each instrument team has developed instruments for other spaceflight missions and is seeking to maximize the heritage for Juno. These missions include New Horizons, Mars Global Surveyor, Cassini and Galileo. A mission to Jupiter has several unique challenges, however, and each team has acknowledged changes from their heritage that are required for Juno. MAG will measure the field to as high as 16 gauss, which is two orders of magnitude higher than on a previous planetary flagship mission (Cassini). In addition, JunoCam was proposed to maximize heritage from MSL, but there are known changes to electronics parts. Solving these challenges makes the payload engineering role interesting.

The Juno thermal range requirements are typically higher than the instrument heritage qualification. This is partially driven by the Juno Mission profile, which flies in as close as 0.88 AU from the Sun, and extends to ~5 AU for Jupiter. The Flight System thermal design is in process. The instrument teams are planning to deliver updated thermal models in the fall of 2007, in advance of instrument PDRs that occur in early 2008. The thermal design will mature by the Project PDR in Summer 2008, and should be finalized by Project CDR about one year later.

In addition to the thermal environment, the radiation environment at Jupiter is a driver for the Juno Mission. Components located outside of the radiation vault experience a high radiation environment. High radiation levels drive parts selection and shielding design complexity. JPL is providing parts evaluation and testing support for instruments, as part of an overall parts program plan. Instrument shielding designs are in process, and are aided by a specially developed radiation control program.

Measure the magnetic field to when the magnitude is as large as 12 gauss.

The Juno requirement is to measure up to 12 gauss; the expected capability is to measure up to 16 gauss, with an accuracy of 0.05% (FGM) or 0.002% (SHM). The Voyager spacecraft carried two sensors, one optimized for low fields (up to 0.5G) and one for high fields (up to 20 G) but this system was not designed for the type of accurate field mapping experiment to be carried out by JUNO. This combination of vector and scalar instruments allows the magnetic field orientation and magnitude requirements of JUNO to be met and is similar to systems used for precision mapping of the earth's magnetic field (for example with the MAGSAT and Oersted satellites). Additional design requirements also come from the need for the magnetic field experiment to cover a wide dynamic range [up to 12 G and seven orders of magnitude below that] and to cope with rapidly changing magnetic fields due to the flight system moving so quickly close to perijove. Current test facilities do not allow accurate calibrations to be made in fields as high as 16 G, so custom solutions (including an accurate high-field coil system) are being developed for JUNO.

Key, but not a driver: Optical coverage

The Juno project has identified the optical coverage requirements as key, but not a driver because the wavelengths are important to achieving the science objectives, but in terms of instrument development the wavelength coverage (78 to 172 nm for UV, 400 to 900 nm for visible, and 2 to 5 µmeter for infrared) is similar to developments for other missions. While these optical requirements may drive each individual instrument, they are not drivers at the Flight System level.

MWR Frequencies

As previously noted, the MWR radiometer frequencies will be 600 MHz, 1.2 GHz, 2.4 GHz, 4.8 GHz, 9.6 GHz, and 22 GHz, each frequency centered to within +/- 10 %. The lowest frequency signal chain requires the largest size antenna and this drives the Flight System configuration. The hexagonal forward deck structure of the S/C was configured to accommodate the multiple MWR antennas (each with an extensive field of regard). The multi-frequency instrument also introduces challenges to the EMC program for Juno (more extensive modeling, analyses and tests will be required at the System level to ensure science objectives will be satisfied).

Achieving thermal stability for MWR

In order to achieve performance requirements, each MWR radiometer will tolerate up to 1 K within +/- 1 hr of perijove during a MWR pass. This requirement is necessary because the radiometer, in simple terms, is a very accurate thermometer (measuring the microwave emissions from Jupiter), so thermal stability allows for the precision necessary to measure water abundance (which is a high priority objective of Juno). The MWR instrument was included in the Juno proposal because of the scientific imperative to measure deep into Jupiter's atmosphere. So, the MWR instrument is particularly critical to the success of the Juno Mission. Robustness studies are on-going for the MWR instrument. Fortunately, the radiation vault is very massive and the power profile inside of the vault is relatively constant. This makes passive accommodation of this thermal stability requirement possible.

Other radiometer instruments at JPL have adopted equally (if not more) challenging requirements with regards to thermal stability. The EOS-MLS instrument invoked a requirement of short-term thermal stability for assemblies within the signal chain of < 0.015 C/min (for durations less than ~90 minutes; those same signal chains adopted longer-term thermal stability requirement of +/- 2 deg. C per month). So, one can see that tight thermal requirements are common for radiometer instrumentation, and are derived from higher-level functional requirements. This particular requirement has been identified as a driver for the Juno radiometer because it is associated with satisfying the precision requirements of the science team.

V. Development Challenges

A set of challenges, risks and watch list items has been developed by the Juno Payload Office. Some of the larger challenges are as follows:

1) Managing ten (10) instruments from many institutions spread across the country and Europe.

As shown in Figure 1, there are many institutions involved with the Juno Payload. The differing cultures of those organizations present challenges to the Payload Office. For instance, SwRI and JHU/APL are large aerospace organizations with well-developed infrastructure, but MSSS is a small business with little to no such equivalent support (not even a separate QA organization). Even significant differences are manifest between JPL and GSFC. Although both appear on the NASA organizational chart, they have developed distinctly different cultures.

To resolve many of these differences, Payload System Management has established contracts, MOUs, and a clearly defined set of deliverables and receivables for each instrument. Routine schedule and technical reporting requirements have been established. The Project traveled to each instrument provider and reviewed JPL's Design Principles and Flight Project Practices against their institutional practices to understand gaps and differences. Furthermore, weekly technical discussions are a standard project tool for ensuring that appropriate development issues are addressed by the Payload System. Instrument teams support routine discussions on the payload, software, radiation, mission design & scenario, and other topics. In addition, the project has established various working groups (EMC, Mag-boom, pointing and alignment, etc.) to ensure that the requirements are satisfied by the contributing institutions.

2) Coordinating the MAG boom among three institutions (LM, GSFC, JPL).

One of the expected challenges is the development and integration of the magnetometer boom and the instrumentation attached to it. The boom itself is one of the larger pieces of structure on the spacecraft, and it must hold the sensors for both the FGM and the SHM. The formulation agreement is that LM is responsible for the boom itself, while GSFC is the lead for MAG (yet JPL has the lead role in developing the SHM as previously indicated). Each of these organizations has its own culture and interests in the success of the Juno project, and keeping those interests properly aligned throughout the development cycle will be a challenge. In order to achieve successful development and integration among these parties, a Mag-boom working group was established, and there will be clearly defined interfaces between each instrument and the spacecraft. The present concept is that FGM & SHM are independently developed at their respective institutions, and then delivered to LM for integration with the Flight System. This will require careful definition and control of mechanical interfaces (for pointing accuracy/reconstruction requirements), as well as accurate processes and procedures utilized during assembly, test, and launch operations. As is usual for a science-driven mission, a rigorous program of verification and validation is expected to confirm customer goals and objectives are satisfied.

3) EMC/EMI/Magnetics

The breadth of EMI requirements is extensive because of the Payload's inclusion of certain instruments (Waves & MAG, in particular). Other instruments bring certain requirements to the table (surface charging limitations for JADE) that were not present on previous missions (LM has no 'heritage' for such a requirement from MRO).

In addition, not all instrument teams have magnetic test facilities, so teams will have to rent or borrow space (JHU/APL is close to GSFC, and MSSS has hired EMI test contractors on previous missions), so the project has confidence that requirements will be verified.

Another key challenge is ensuring that quality measurements are produced in the high magnetic field of Jupiter. In order to mitigate this, the project has established Mag/EMC/EMI cleanliness and test programs, under the auspices of a Magnetics Control Board (which also oversees the modeling and analysis of electromagnetic effects), and the co-investigator for MAG has been a valuable advisor to the Flight System designers with respect to magnetics. Magnetics workshops have been and will be held throughout the formulation and implementation phases.

4) Contamination control for MCPs.

Multiple instruments within the payload (JEDI, JADE, and UVS) include micro-channel plates (MCPs) and MCPs are known to be highly contamination-sensitive. The Flight System design (e.g. thruster locations) and ATLO flow must account for the needs of the MCPs vis-à-vis contamination control. Appropriate science requirements have been documented, and analysis is needed to gain confidence that MCP performance will not be unduly degraded. The resulting design trade-offs could impact Flight System mass and the instrument FOVs. Thruster locations could be adjusted, as required to ensure all instruments meet science performance requirements. Analyses will be provided to instrument teams for their review (to ensure requirements are met). If thruster placement alone cannot achieve contamination requirements, plume shields could be added to the spacecraft design; such designs would be well reviewed at PDR.

5) Burst Mode

Juno has designed in a special feature among the instruments which is called "burst mode". It is a feature whereby high-rate data is collected for very short periods of time, with only higher quality data downlinked. The instruments that participate in burst data collection are JADE and Waves, with UVS using a data management scheme that is based on the same principles. It is a special feature because the information from one instrument (Waves) is used to on-board-process the data from another (JADE). What makes it especially intriguing is that the processing is done by the S/C, not by either of the two instruments. Design features like this typically get special attention on JPL missions because of the general principle that the failure of a single instrument should not propagate to another. In this case, burst mode can be enabled or disabled for each instrument, thereby creating isolation.

Summary

The Juno Payload is well on its way towards completing a unique set of key and driving requirements as well as addressing a challenging set of development risks in preparation for the Project Confirmation Review in mid 2008.

Appendix

This appendix includes acronyms used in this paper.

A. Acronyms

AO	Announcement of Opportunity
ASC	Advanced Stellar Compass
ASI	Agenzia Spaziale Italiana (Italian Space Agency)
ATLO	Assembly, Test, and Launch Operations
AU	Astronomical Units
CSR	Concept Study Report
DSM	Deep Space Maneuver
DTU	Danish Technical University
EFB	Earth FlyBy
E/PO	Education and Public Outreach
FGM	FluxGate Magnetometer
FOV	Field of View
G	Gauss
GA	Galileo Avionica
GS	Gravity Science
GSFC	Goddard Space Flight Center
HGA	High Gain Antenna
JADE	Jovian Auroral Distribution Experiment
JEDI	Jupiter Energetic-particle Detector Instrument
JHU/APL	Johns Hopkins University/Applied Physics Lab
JIRAM	Juno InfraRed Auroral Mapper
JOI	Jupiter Orbit Insertion
JPET	Juno Payload Engineering Team
JPL	Jet Propulsion Laboratory
KaT	Ka-band Translator
LGA	Low Gain Antenna
LM	Lockheed Martin
MAG	Magnetometer (includes FGM & SHM)
MCP	Micro-channel plate
MGS	Mars Global Surveyor
MSC	Magnetic Search Coil
MSSS	Malin Space Science Systems
MWR	MicroWave Radiometer
MRO	Mars Reconnaissance Orbiter
NASA	National Aeronautics and Space Administration
PJ	Peri-Jove
PLD	Payload
PRM	Period Reduction Maneuver
RCS	Reaction Control System
R_J	Radius of Jupiter
S/C	Spacecraft
SHM	Scalar Helium Magnetometer

SPF	Single Point Failure
SwRI	Southwest Research Institute
UVS	UltraViolet Spectrograph

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