PLANETARY PROBE SCIENCE PAYLOAD MISSION DESIGN TOOL

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ABSTRACT

Throughout the development of planetary probe missions from initial concepts, identification of flight qualified hardware components that meet mission requirements is crucial to mission success. Scientific measurement requirements are determined from the initial science mission concept of operation, goals and objectives. From the science payload, design of the spacecraft systems can be achieved.

The Science Payload Design Evaluation Tool (SPDE) presented in this paper, comprises a database collection of individual sensor modules of commercial, space-rated and flight-proven components. The tool developed determines the required components based on the mission concept of operations. Information on the planetary probe's mission objective and types of science data to be collected, along with payload limits is entered into the main program interface.

The Preliminary Integrated Spacecraft Modeling (PrISM) Tool extends the design capability to the spacecraft level and designs the subsystem properties. Mass, power, and volume properties are generated from the payload design to develop the associated mission parameters.

1. INTRODUCTION

The primary interest in development of this program came from the short course on In-Situ Instruments for Planetary Probes and Aerial Platforms hosted as part of the 4th International Planetary Probe Workshop [1]. Attendees were given a mass and power budget for a planetary probe mission that used an aerial platform, and were tasked to develop a sensor package that would meet the mission requirement and fit within the payload constraints. During the initial planning stages, long before a mission is launched, a series of studies are conducted to create a sensor package tailored to meet the mission requirements. Flight hardware components are chosen to survive the operating environment and meet mission requirements.

Design of the sensor payload package for any mission addresses several issues. The final optimal payload configuration is a result of individual case studies and design engineering studies. The scope of the tool, is limited to optimization techniques within the sensor payload, however, higher system level criteria may impact the component level design, resulting in a different component selection. Human decisions are still included in the design process, as final selection between competing elements is made. The decision to use one component over another can arise from many factors – functionality, heritage, Technology Readiness Level (TRL) [2], etc. The objective of this work is to combine all of the selection techniques for mission hardware into a single tool that can be used to generate a preliminary sensor package and spacecraft design.

2. METHODOLOGY

The component selection algorithms implemented in this tool trades sensor component characteristics (operational parameters such as range, performance, weight, accuracy, etc.) to arrive at an optimum component choice, based on a set of mission sensor requirements (e.g., planetary atmospheric data collection). Initial configurations are developed using top level mission requirements. As the solution for each sensor type progresses, the properties of the sensor are evaluated at finer levels of analysis. If a component no longer satisfies a requirement it is eliminated from analysis. If no suitable solution can be determined, work-around strategies must be made to find a way to modify existing hardware to satisfy the mission requirements, either via specialized custom built sensors, modification of commercially available components to allow it to meet requirements, or by making a modification to the mission requirement. The end result of this design tool for each type of mission science data is a unique commercially available sensor component.

A database of commercially available components is developed for each type of sensor. The down-selection process will employ several methods to eliminate incompatible sensors. Primary selection methods are based on the operational range of the sensor type (e.g.,

temperature range for thermocouples, atmospheric gasses for mass spectrometers). Special consideration is given to heritage system components, to further select from multiple sensors that operate over similar operational ranges. Use of heritage materials implies a high level of technological development behind the sensor. The TRL employed in a sensor's design, relates the development level and risk associated with the hardware. While technology with a higher TRL is desirable, there are other advantages to a lower TRL device. Similar devices could have a lower TRL, but be significantly lighter. However, the lower TRL device has an increased level of inherent risk in its use, compared to a more mature design. Multi-role components can also be evaluated for their useful properties. These types of units complete the tasks assigned to multiple sensors with the benefit of a single unit capable of recording several data types. The use of these selection factors will allow for the determination of a component that will meet the mission sensor requirements.

As each component is selected for the sensor package, additional interactions between sensors will come into play. Design constraints may limit the use of certain types of sensors. Once a preliminary sensor design package has been completed, interactions between sensors at a system level may determine if any components are incompatible with other sensors. If this condition occurs, individual sensor requirements will have be modified and evaluated via another iteration with all the sensors until the sensors are compatible with each other and a final design solutions exists, or if the program determines that there is no commercially existing solution that meets the mission requirements, a "best solution" option is presented, modified to a custom sensor to meet the mission goal.

3. SPDE TOOL

The Science Payload Design Evaluator (SPDE) Tool builds upon the sensor payload tool presented at the 6th International Planetary Probe Workshop held in Atlanta, Georgia. The tool adds a GUI interface wrapper, shown in Figure 1, around the previous In-Situ Sensor Payload Optimization (ISSPO) Program [3] and incorporates additional sensor modules into the tools design framework. SPDE was developed to allow a dual operation mode for novice or experienced users. For new users of the tool the GUI design aids the setup of the sensor payload and compiles all the required data into the design file to execute the main program. Upon familiarization with the tool users can supply the needed data for the sensor design and execute the tool without the use of the GUI. Program operation will continue seamlessly via ether method and develop the needed sensor package.

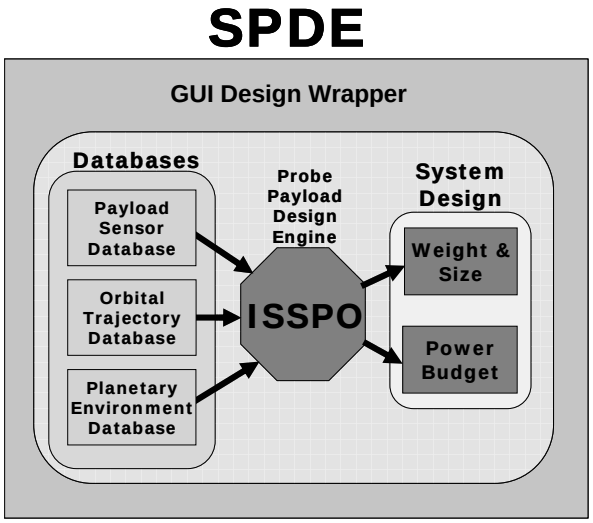

Fig. 1. Science Payload Design Evaluation (SPDE) Tool Layout

3.1 SPDE Program

The SPDE routine is the primary program call entered at the MatLAB command prompt. From here, the input data is loaded to the main program and the sensor payload is configured from the sensor modules. Each module contains its own set of variables needed by the program. At the end of each module, the relevant data is written to a '.mat' binary data file. In the main SPDE program, the data file is loaded into memory and the data is made available for all subroutines to use. A summary program flowchart in Figure 2 outlines the operation of the SPDE Tool using the GUI to setup the design file and execute the program.

The SPDE Program comprises multiple subroutines being called from the main program. Each subroutine is called and returns specific pieces of data back to the main program. Sensor type subroutines are developed as self contained models only requiring inputs from the main program to select the correct component or, when necessary, obtain data from another module to select the component. The subroutine for each sensor type is only called if a corresponding type of data is requested in the main.

This modular development allows for the program to include all sensor types, yet reduce running time to only relevant sensor types. Many planetary science missions feature a basic atmospheric properties sensor pack that monitor temperature, pressure, density, etc. Within the SPDE tool these atmospheric sensors have been coupled into a single input option selection that calls all the individual sensors automatically. The function and properties of each of the SPDE Tool

subroutines is discussed [3] and operates identically either via the GUI or input file option.

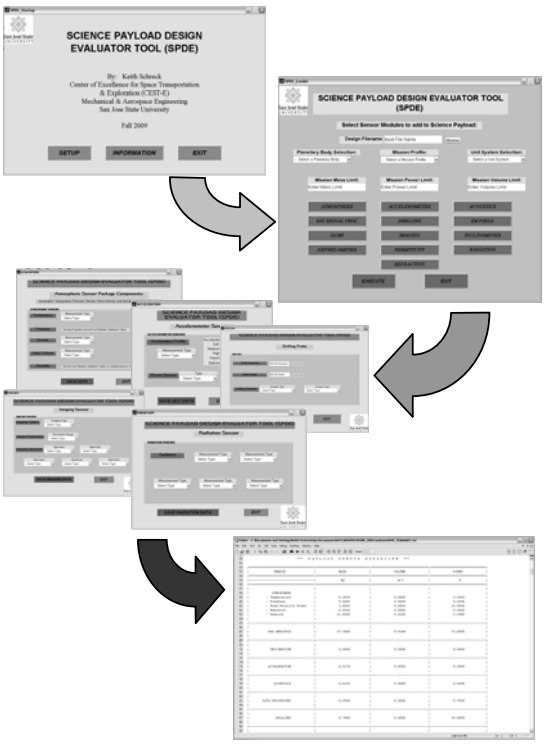

Fig. 2. SPDE Tool GUI Operation

4. HUYGENS PROBE BENCHMARK CASE

As a test case to validate the methodology developed within the original ISSPO program, the interplanetary probe mission to Saturn's Titan moon carried out by the Huygens probe was used. Development of the SPDE GUI configuration, used the same test case configuration to verify the function of the tool

This spacecraft consisted of several complex sensor packages with independent mission objectives. [4, 5, 6] Data on the spacecraft systems and top level packages is obtained from various references to determine which of the hardware components were based on available components, and which were custom designs built to suit a specific science goal for this mission.

Custom designed sensor configurations will always be required when the mission science question is truly unique or the level of fidelity of a commercially developed sensor is not readily available. In this case an available sensor may only need slight modification by the developer to meet the mission objective. The base model design can act as a reference point that can be modified to handle mission requirements that it was not originally designed to meet. In evaluating the component designs for the different sensor packages on the Huygens Lander, there is a combination of commercially available sensors, modified versions, and custom functioning units used.

Each subsystem of the Huygens Planetary Probe was analyzed separately as a stand alone design system. Six primary science packages comprised the science payload for the entire mission. The requirements for each package is described in turn and evaluated using the mass and power limits for each subsystem. A comparison of the results to the published data available is made. Despite the large number of instruments contained in the science payload, it represented only a small portion of the total spacecraft mass and volume. The mission profile was for a short lifetime to collect and relay the data thus a number of components has redundant systems or multiple ways to obtain the different data in case a system failed.

4.1 Huygens Descent Imager / Spectral Radiometer (DISR)

The Descent Imager / Spectral Radiometer (DISR) sensor suite onboard the Huygens probe recorded images as the probe entered the Titan atmosphere. It was responsible for recording both descent imagery to monitor the surrounding terrain during the descent phase to provide background context, and upward looking data to observe the optical properties of the atmosphere.

To meet all the optical observation requirements commercial grade CCD detectors were coupled to multiple camera lenses, each built to meet a specific observation requirement. This configuration allowed for a higher instrument density focusing multiple imaging devices onto a single CCD array. The custom configuration of the lenses does not represent a commercial viable solution for optical data recording. In this case the SPDE tool was tasked to select a CCD based on the required types and amount of data to be recorded by the probe during the mission timeframe. Configuration of the SPDE GUI input for this sensor configuration is shown in Figure 3.

Based on these criteria for a CCD array design, the SPDE tool determined a compatible CCD array configuration to the design flown on Huygens. The output summary of the sensor data is shown in Figure 4. The selected design has a larger CCD area, and offers the same frame transfer and binning capability of the model flown on Huygens. The model 424 CCD array is a flight proven model developed for NASA's Deep Impact Mission. [7]

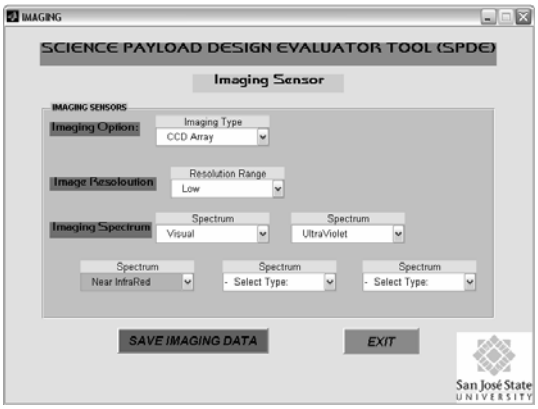

Fig. 3. SPDE Tool - Huygens DISR Inputs

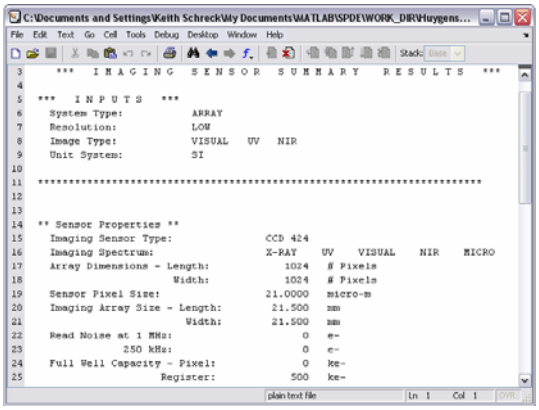

Fig. 4. SPDE Tool - Huygens DISR Results

4.2 Doppler Wind Experiment (DWE)

The Doppler Wind Experiment (DWE) carried aboard the Huygens probe is used to determine wind speeds in the atmosphere as the probe descended towards Titan's Surface. The DWE consists of two Ultra-Stable Oscillators, one carried aboard the Huygens Probe, while the other remains aboard the Cassini Orbiter. Measured wind velocity is back calculated from Doppler shifts in the transmitted radio signal frequencies between the two receiver transmitters.

Based on the different sensor types in the database and the planetary environmental properties that the sensor must cope with SPDE determined a sensor package with similar properties to the actual flight unit. The DWE package [8] built by Daimler-Benz Aerospace (DASA), now EADS Germany used a commercially developed space-qualified rubidium oscillator built by Ball Efratom Elektronik GmbH. Selection of the DWE properties is shown in Figure 5.

There are slight performance differences between the actual flight unit and the SPDE design solution. The largest differences is the unit is about half the weight of the Huygens model but consumes more power at max input, but better matches the sensor performance during steady state operation. The model has a significantly shorter warm up period resulting in lower total power consumption. Brief summary results on the DWE sensor package are provided in Figure 6.

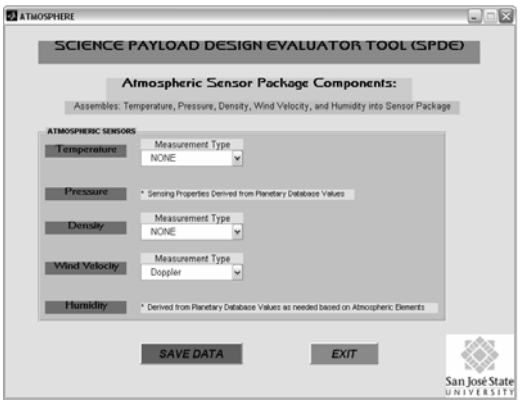

Fig. 5. SPDE Tool - Huygens DWE Inputs

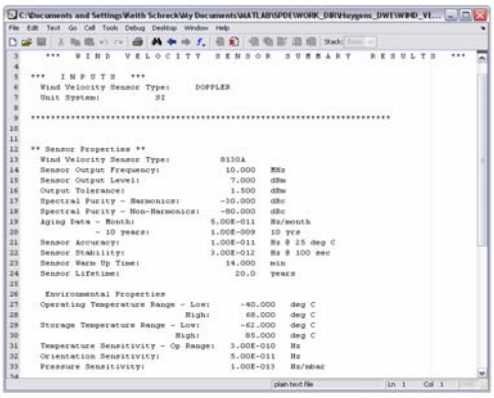

Fig. 6. SPDE Tool - Huygens DWE Results

4.3 Huygens Gas Chromatograph Mass Spectrometer (GCMS)

Use of Gas Chromatograph Mass Spectrometer (GCMS) in planetary missions is a relatively new option. Typically these units have been custom built and designed specifically for a single mission. As such, a database of flight rated configurations is limited. Numerous laboratory models exist but are not built with the same considerations that are given to flight systems. In space missions mass, power, and volume are all at a premium whereas laboratory models do not have these constraints. The configuration flown on the Huygens probe is a custom configuration due to the payload constraints but based on commercially available individual products. The completed flight unit now represents a flight proven configuration with enough available performance data that it can represent a stand alone product to be used on other future missions with minimal changes for other planetary atmospheres. The GCMS onboard Huygens was built by NASA's Goddard Space Flight Center (GSFC), [9,

10, 11] and can be made available to reproduce for any future missions needing a similar device.

The flight unit is comprised of commercially available products including five ion sources attached to the mass spectrometer. The different components were machined to fit and assembled together to create the final flight unit. The final assembled version houses all the sensor components and associated electrical hardware to sample the Titan atmosphere and analyze the data. Shown in Figure 7 and 8, are the SPDE GCMS Huygens Probe inputs and results, respectively.

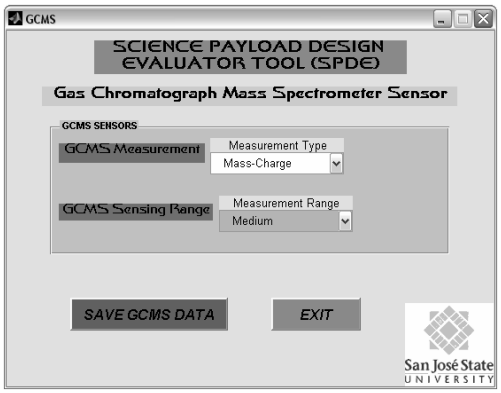

Fig. 7. SPDE Tool - Huygens GCMS Inputs

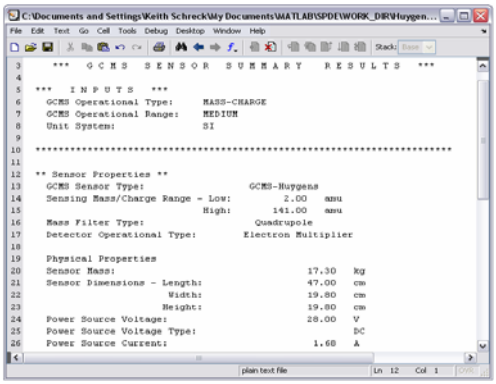

Fig. 8. SPDE Tool - Huygens GCMS Results

4.4 Huygens Atmosphere Structure Instrument (HASI)

The Huygens Atmosphere Structure Instrument (HASI) is a key multi-sensor component to mapping the Titan atmosphere. It incorporated multiple atmospheric sensor elements into an overall package that would monitor most atmospheric properties during the planetary entry. Sensors within this package have been categorized into the type of environmental data that is returned, including: acceleration, pressure, temperature, and Permittivity, Wave, and Altimetry. Mission science objectives for HASI sensor suite was the determination of density, temperature, and pressure through the descent profile to the surface, determine the nature of the surface contact, solid or liquid, atmospheric electrical conductivity, electric fields and atmospheric lightning, and surface topography by monitoring surface dielectric fields. Within the design of this sensor package a certain amount of redundancy is included; in case a single element failed the secondary unit would continue to provide information. Configuration of the sensor package inputs is shown in Figure 9.

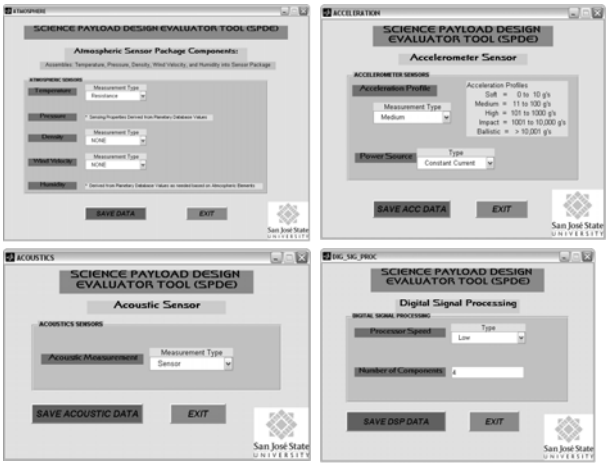

Fig.9. SPDE Tool - Huygens HASI Inputs

A summary of the different science sensor system components is detailed in Table 1. The sensors in the PWA subsystem or mounted external to the spacecraft, and shielded from the electric field generated within the probe body by all the electronic components.

Table 1 SPDE Tool - HASI Sensor Package Results

HASI Sensor Package Components		
Sensor Package	Flight Unit	SPDE Results
Accelerometer – 3 axis servo	Sundstrand QA-2000-030	QA2000-030
Accelerometer - piezoresistive	Endevco 7264A-2000T	Endevco 7264A-2000T
Pressure Profile Instrument	Vaisala – Barocap	Series 48-0025
Temperature Sensor	dual element platinum resistance thermometers Rosemount Aerospace Inc.	Goodrich Model 0146MD
PWA – Acoustic Sensor	Kulite CT-190M	Kulite CT-190M
PWA – Digital Signal Processor (FFT)	Analog Devices ADSP-2100A	ADSP-2100A

4.5 Huygens Surface Science Package (SSP)

The Surface Science Package (SSP) carried aboard the Huygens Titan probe comprised nine different sensors

monitoring seven different types of planetary science data. The goal of the SSP was to measure and determine the nature of Titan's surface properties. Based on the summary of mission requirements input into the SPDE program, a summary sensor design package is detailed in Table 2.

Table 2 SPDE Tool - Huygens SSP Sensor Component Comparison

SSP Sensor Components		
Sensor	Flight Unit	SPDE Results
Accelerometer – Impact penetrometer ACC-E	Piezoelectric Ceramic PZT-5A	N/A Custom Design
Accelerometer - Impact accelerometer ACC-I	Endevco 2271AM20 0 – 100 g's	Endevco 2271AM20
Tilt Sensor TIL	Spectron L-211U +/- 60°	Spectron L-211U
Temperature Sensor THP	Hot Wire 65 – 100 K	M-0146MD
Velocity of Sound API-V	Piezoelectric Transducers – 2 150 – 2000 m/s	Physical Acoustics R80 Alpha

Information on commercial components used in the SSP is scarce and several of the sensors are approximated in the final SPDE design solution by similar components. Some components found in the SSP design represent custom design solutions for the specific to the Huygens probe application.

4.6 SPDE Huygens Summary

The results of the ISSPO tool comparison with the SPDE GUI based configuration of the Huygens probe mission gave identical results. Given the mission requirements for science data and the sensor package power and mass limits, the SPDE tool was able to assemble a sensor configuration capable of meeting the requirements. Data on sensor configurations is based on product specified data sheets available from commercial suppliers. Variations in reported data amongst different vendors make for difficult product comparisons. Data not available for all sensor configurations amongst suppliers is zeroed out within the sensor databases.

Custom configured sensors for some of the sensor packages carried aboard the Huygens probe were not included since they represent a single point design, or use of the sensor has not been extensive enough to develop a database of sensor configurations. Additional space missions with similar science objectives are required to develop additional sensor databases.

5. SPACECRAFT DESIGN TOOL

On its own the payload for any planetary science mission, can not complete its task. The payload can not achieve its goals without a spacecraft to provide all the necessary interfaces to the payload. The SPDE tool can provide the design for the necessary sensor packages based on the planetary science mission requirements, but to support the mission payload, a spacecraft design is required. The spacecraft needs to provide the payload with everything it needs to complete the mission, from power to data handling, to commands to direct the mission operation. With the science payload designed for a given mission, the next element is to design the spacecraft systems [12] and develop the mass, power, volume budgets, for each system and design the performance of the systems. Basic performance aspects of each of the spacecrafts systems are merged in the Preliminary Integrated Spacecraft Modeling (PrISM) Tool.

5.1 PrISM Design Tool

The PrISM Tool represents a follow on design tool to SPDE's design algorithms. It extends the design capability for a planetary science mission out beyond the payload, to the spacecraft and its related systems shown in Figure 10. PrISM operation is similar to the execution of the SPDE Tool. Program input are read in from a data file and loaded into the simulation during execution. Modules from the main program are executed to size the total mass, power, volume, power system, communications, and costs of the program.

Minimum program inputs include the basic properties of the payload of the spacecraft – mass, power, and volume. A default set of design values is loaded to provide a spacecraft design. Each value can be individually adjusted to calibrate the design of the vehicle to a certain mission class.

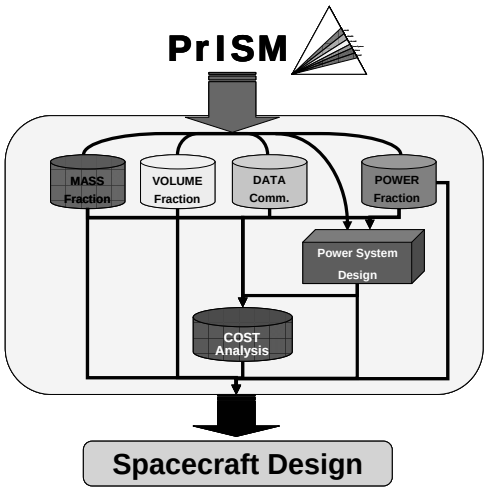

Fig. 10. PrISM Tool Functional Flowchart

5.2 PrISM Input File Verification

Each module within the PrISM tool contains a dataset of internal program variables. The values are loaded into program memory as they are called within the program. Modules require different data as the user selects different options within the design framework of the program. Program inputs are rigorously processed prior to module execution to verify that all the needed inputs are correctly set for the different design options within the tool. Any data missing or undefined prior to the data processor operation, executes an error program, detailing the nature of the program error, and terminates the program.

5.3 PrISM Mass Fraction

The MASS_FRACTION subroutine assembles the mass breakdown of the spacecraft systems based on the given size of the mission payload. System component weights are based on known ratios of subsystems weights from a database of past flown mission designs. The fixed component ratios of each of the system elements are set within the program, but can be altered to represent new design technologies, or spacecraft designed for vastly different mission concepts.

The final system weights are calculated based on the default values or on a known payload fraction of the overall system. Subsystem weights are written out to a '.mat' file and loaded back into the main program, ready to be called by the other modules in the program. Mass data is generated for each of the primary spacecraft systems as baseline values, and includes system mass margins based on the levels of technology incorporated into the design and the design maturity.

5.4 PrISM Power Fraction

The POWER_FRACTION subroutine generates the total mission power allocation for the spacecraft and power needed to operate each of the subsystems. Subsystem power requirements are based on a database of past mission designs of power consumption ranges for each system. Power requirement ranges of each of the spacecraft subsystems are set within the program, but can be altered to represent different spacecraft design scopes.

Final system power requirements are calculated from the payload power value and power ratios for each of the different spacecraft systems. Subsystem power needs are written out to a '.mat' file and loaded back into the main program, to be used by other modules in the program. Power values are generated for each of the primary spacecraft systems as baseline values, including power margins based on technology incorporated into the design, design maturity, and the expected operational power load cycle requirements.

5.5 PrISM Volume Fraction

The VOLUME_FRACTION subroutine allocates volume for each of the spacecraft subsystems. Subsystem volume requirements are based on a range of design densities of the overall spacecraft mass. Extrapolations are then made for the vehicle's body area and rough linear dimensions for the spacecraft's size. Volume requirements are calculated at the rolled-up spacecraft level from the total spacecraft mass with design margins. Volume calculation results are written out to a '.mat' file and loaded back into the main program.

5.6 PrISM Power System Design

One of the components in a mission design, most susceptible to changes in mission technology or mission requirements is the power system of the spacecraft. Selection of the design of the power system for any mission is highly dependent upon the nature and scope of the mission. The mass, power consumption and volume requirements of the spacecrafts power system can vary drastically based on mission lifetime and power requirements of the mission. The PrISM tool's POWER_SYSTEM_-DESIGN subroutine allows for additional analytical options for different technologies to power the spacecraft. Power system technology options within the design subroutine allow for evaluation of today's most commonly used systems. The tool allows for selection between power system designs for short and long term mission lifetimes, or constant and regenerative systems.

Use of the Primary Battery option is common for missions of short lifetimes, where mass and volume are premiums and power is needed for only short term or single events in the mission timeline. Solar Panel and Secondary Battery power options have been the primary option for most planetary missions with long lifetimes, or close proximity to the sun to recharge its batteries for use during eclipse periods. Additional power system options within the module allow selection of smaller continuous power generation systems, including Fuel Cells, Solar Thermal Systems, Radioisotope Thermoelectric Generators (RTG's), or Nuclear Reactors. These systems are best suited for long term missions where higher power levels are required during eclipse periods that can not be supported by batteries, or missions to distant locations where solar power options are unfeasible.

Based on the type of power system selected additional inputs are required to define the systems properties. Use of the solar panels, primary or secondary battery options requires additional inputs to define the type of technology used. For solar panels, a database of available materials allows the selection of a range of materials from low cost, low efficiency silicon panels, to more expensive, high efficiency gallium arsenide. Selection of materials also includes materials nearing the limits of laboratory research grade multi-junction cell material. Battery technology for primary and secondary options includes commercially available options with well defined performance characteristics, as well as high energy density lithium battery design technology. Based on the type of power system used program output will vary from the minimum system mass to the needed power requirement during eclipse periods to end of life power requirement for solar array systems and needed solar panel area to meet the power requirements.

5.7 PrISM Space Cost Modeler

A final key element in the design of any mission is the cost. Data on the mission payload is used to size the corresponding spacecraft for the mission. In the PrISM cost modeling subroutine, data from the design modules for each subsystem is entered into a database of cost scaling factors based for each system. Cost data for the design is broken down to research development testing and evaluation, first unit production cost, and additional units. Estimates of program support including integration assembly and test, program level support, ground support equipment and launch integration and operations support are detailed as part of the total mission cost.

6. PrISM DEVELOPMENT CASE

Each of the PrISM modules was developed, using generalized equations for the design of the various subsystems. Settings and calibration factors for each of the modules can be adjusted to model different designs. Once calibrated to the design of a specific mission type, new spacecraft designs can be made based on requirements, hardware technology, and design relations.

Design concepts for two different classes of missions were used as calibration points. Both cases represent different phases of the overall mission. In this example, the Pioneer Venus comprised several different vehicle designs, and mission types. The mission involved a single spacecraft carrying the Pioneer Venus Orbiter, and the Multiprobe Bus – carrying one Venus Large Probe and three Venus Small Probes. Here, only the Venus Orbiter, and the Venus Small Probe designs are evaluated. Each of these designs is discussed in turn.

6.1 Pioneer Venus Orbiter

The Pioneer Venus Orbiter carried a suite of 12 sensor packages for its payload, and separated from the Venus Multiprobe after the deployment of the three small and one large probe. The Orbiter entered Venus orbit on December 4, 1978, and was placed into a highly elliptical orbit (241 km x 66,000 km) with a 24 hour orbital period. The end of the Venus Orbiter mission came in May 1992 [13] as the periapsis was altered to 150 – 250 km; its fuel was depleted, and plunged into the Venus atmosphere in August.

The Orbiter mission was to analyze the Venus's atmosphere and relay data back to Earth over the course of mission lifetime. The payload requirements for the Orbiter, total 45 kg, 60.3 W power [14], and 60,107 cm^3 volume. [15] A comparison of the PrISM Orbiter design to the flight configuration is shown in Table 3.

Table 3 PrISM Tool – Pioneer Venus Orbiter Spacecraft Design Comparison

Physical Properties	PrISM Design	Pioneer Design	Units
Payload Mass	45	45	kg
Spacecraft Total	501	517	kg
Linear Dimension	1.99	2.5	m
Surface Area	3.94	9.42*	m^2
Spacecraft Volume	5.01	5.89*	m^3

* Value calculated from probe diameter

To cope with the long tem nature of the mission and the periodic eclipse the Pioneer Orbiter uses a dual power source system to provide energy to the payload and all the spacecraft systems, with results shown in Table 4. A series of solar cells wrap around the cylindrical surface of the obiter constantly providing power when in sunlight. During the period in eclipse a pair of nickel-cadmium rechargeable batteries provides power to the spacecraft bus.

Table 4 PrISM Tool – Pioneer Venus Orbiter Spacecraft Power System Design Comparison

Power System Properties	PrISM Design	Pioneer Design	Units
Payload Power	60.3	60.3	W
Spacecraft Power Total	301.5	312	W
Battery Type	Ni-Cd	Ni-CD	
Probe Bus voltage	28	28	V
Total Battery Capacity	255.74	252	W-hr
Battery Depth of Discharge	63.6	60	%
Battery Capacity	9.13	2 x 7.5	A-hr
Solar Array Material	Silicon	Silicon	
Orbital Period	24	24	hrs
Eclipse Period	26	26	min
Solar Array Area	3.57	7.4	m^2

Due to the cylindrical nature of the Orbiter spacecraft and the body mounted solar cells, at any time only half of the total surface area is exposed to the sun to generate electrical power. The required surface area is even further reduced due to the cosine effect of sunlight striking the cells at near parallel angles.

Comparison of the design between the PrISM Tool and the Pioneer Venus Orbiter agrees well with the available design for mass budget, power budget, and power system. Cost breakdown of the mission including its research and development, assembly and testing, and mission operations was not available so a cost model comparison could not be performed.

6.2 Pioneer Venus Small Probes

Attached to the Pioneer Venus Multiprobe were four separate reentry vehicles: one Pioneer Large probe and three Pioneer Small Probes. The small probe contains a total of seven different sensor elements organized into a couple of small packages. Mission design for the small probe separates from the Multiprobe Bus 19 days before arrival at Venus. Mission duration was expected to last from reentry to impact. The small probes followed a ballistic trajectory to impact on the surface. Data from the mission was only transmitted during the reentry phase. The mission was to survive the impact and record data for a long as possible before succumbing to the hostile Venus environment. The spacecraft contained a small payload, and needed only minimal power for a transmitter to send the data back to Earth. Based on the small probes payload properties for mass and power, the results of the PrISM tool for this design are shown in Table 5.

From the resulting design, assuming the payload constitutes five percent of the spacecraft mass, results in about a 1.6 % error in the total spacecraft mass. Differences exist in the noted total mass of the probe, either 90 or 94 kg [4, 14, 16]. The differences in published masses could be due to the weight of the front aeroshell and heat shield on the probe as it does not separate from the probe during the entry, descent, and landing (EDL) phase.

Table 5 PrISM Tool – Pioneer Venus Small Probe Spacecraft Design Comparison

Physical Properties	PrISM Design	Pioneer Design	Units
Payload Mass	5	5	kg
Spacecraft Total	95.54	94	kg
Linear Dimension	1.14	0.8	m
Surface Area	1.31	2*	m^2
Spacecraft Volume	0.96	0.27*	m^3

* Value calculated from probe diameter

Data on the geometry for the spacecraft has a higher error in the results, as the calculations are based on average densities from multiple spacecraft mission types. Results for these calculations can be adjusted by scaling the associated reference densities in the input file. Pioneer Venus Small Probes were highly efficient spherical designs instead of cubic, or rectangular prism shapes.

The power system for this spacecraft is a simple primary battery design to power the systems from the Pioneer Multibus spacecraft separation to impact. On the small probe only the science payload required any power, used to transmit the data back to Earth. A silver-zinc battery pack provided the power regulated at 22 V [4] to the system to transmit the data. Based on this design information a comparison of the resulting PrISM design and the flight system is shown in Table 6.

Table 6 PrISM Tool – Pioneer Venus Small Probe Spacecraft Power System Design Comparison

Power System Properties	PrISM Design	Pioneer Design	Units
Payload Power	10	10	W
Spacecraft Power Total	10	10	W
Battery Type	Ag-Zn	Ag-Zn	
Probe Bus voltage	22	22	V
Total Battery Capacity	240	241	W-hr
Battery Capacity	10.97	11	A-hr

Data transmission during the EDL is handled in real time from the sensor packages. Data is instantly transmitted back to Earth at 64 bits/sec, since at any time the mission could fail, it was relayed back to ensure that the information was recorded on Earth. During reentry, a period of plasma blackout was expected as the probe descended through to the lower atmosphere, to keep transmitting data, a small solid state drive was employed to store data during the plasma blackout, and then transmit once it had passed. The data storage system was large enough to handle the data at a lower rate (16 bits/sec) [14] though the blackout and transmitted once it had dissipated.

Comparison between the PrISM Tool and the Pioneer Venus Small Probe compares well with the available design for mass, power, and data recording systems. Volume calculations here show higher error margins as the equations are based on average density values, for space missions. The design for the small probes was based on the much higher pressure Venus atmosphere and thus required a stronger shell to survive the atmospheric descent. Cost breakdown of the mission including its research and development, assembly and testing, and mission operations was not available so a cost model comparison could not be performed.

7. MARS PHOBOS MOON EXPLORATION MISSION

Recent interest in visiting nearby asteroids, comets, and moons, poses a unique set of design constraints for a mission. The relatively small target location requires a high level of landing precision, and precise orbital maneuvers to perform the correct orbit insertion. Due to the small nature of the object, the need to cope with high aerodynamic re-entry effects is minimized as there is no need for large delta-V changes. However, with no atmosphere around all maneuvers must be propellant based requiring additional mass. The small planetary mass also reduces launch velocity requirements enabling a possible sample return mission to answer many questions.

Missions to the Martian system would provide additional valuable information to use for future mission planning and eventual manned missions. A mission to a Martian moon would act as a technology testbed for manned missions to asteroids and build upon the network of spacecraft in the Martian system. The moon, Phobos, offers a platform to further expand our knowledge of the composition of Mars, its moons, and their formation. Martian meteorites, possibly containing organic material has been found on Earth, examination of pure surface and core samples could resolve debates about the formation of Mars, the capture and creation of its moons, and the possibility of past life on Mars.

A Phobos Moon mission designed with a full sensor suite to record and analyze the environment, could provide bountiful information on the development of the Martian System, answer questions about organic material on other planets, and provide additional resources near Mars to enhance data collection. With Phobos tidally locked to Mars, the moon presents a side to Mars, and a side to space. The material on each of these sides can be different due to the formation of the moon and the environment they have been exposed to since the formation of the moon. A mission scenario similar to the mars rovers would allow simultaneous exploration of both sides of the moon and return significant scientific information.

A mission science package is assembled to perform a complete analysis of the moon, including an atmosphere package, soil and surface analysis, gas analysis, visual mapping, magnetic field mapping, and observation of background radiation. Table 7 shows the basic elements of the sensor packages required to complete the mission scenario.

Based on the desired science payload for the mission a detailed sensor package is assembled using the SPDE design environment. From the selected sensor payload options the resulting SPDE payload design is shown in Table 8. Components were selected based on the known properties of the mission location and the type of science information returned. From the sensor package, a spacecraft design concept can be laid out.

Table 7 Phobos Exploration Mission

Phobos Explorer Mission Objectives	
Mission Data	Objective Reasoning
ATMOSPHERIC ANALYSIS	Provide Atmospheric Properties: Temperature, Pressure, Density, Winds
ACCELERATION	Provide descent deceleration profile information and use for event sequence timings
DRILLING	Mine and excavate surface regolith to determine composition
EM FIELD	Map planetary magnetic field to determine moon core composition
GAS ANALYSIS	Analyze atmosphere and detect chemicals in soil samples
RADIATION	Detect charged particle occurrences on the moon, map out background radiation environment
OPTICS	Provide in-situ visual observations of local terrain in multiple wavelengths

Table 8 Phobos Exploration Mission Payload Design

Phobos Explorer Mission Payload			
Mission Data	System Mass (kg)	System Power (W)	System Volume (m^3)
ATMOSPHERIC ANALYSIS	28.0004	0.536	0.0201
ACCELERATION	0.0992	0	0
DRILLING	4	30	0.0063
EM FIELD	1.08	0	0.0016
GAS ANALYSIS	2.72	0	0.0038
RADIATION	7	15	0.0067
OPTICS	9.3	0	0.0048
Payload Total	52.1996	45.536	0.0433

Design of the spacecraft is then performed by the PrISM tool, determining the mass, power and volume budgets needed for the mission. With the Phobos Explorer Moon Mission a dual power system of solar cells and secondary batteries is used. This will ensure power during periods of planetary eclipse. Summary design results for the spacecraft subsystems are in Table 9.

Design parameters for the spacecraft power system were adapted from the Pioneer Venus Orbiter design.

Solar Cell materials were updated from silicon cells to higher efficiency gallium arsenide cells. Power requirements for the mission assumed full power available to all the payload components during the period in solar eclipse.

The design results from the tool give a preliminary estimate of the scale of the mission and the weight, power, and volume of the mission. Estimates are further refined with additional studies to determine the hardware and components needed.

Table 9 Phobos Exploration Mission Spacecraft Design

Phobos Explorer Mission Spacecraft		
System Properties	System Mass (kg)	System Power (W)
Payload Properties	52.2	45.54
Attitude, Determination & Control System	43.96	26.10
Command & Data Handling	22.67	10.84
Power	153.30	50.26
Propulsion	20.33	8.44
Structure	119.24	0
Thermal	18.68	8.44
Tracking, Telemetry & Command	18.54	32.52
Subsystem Totals	396.72	136.61
Design Margins	112.33	45.54
Spacecraft Totals	561.15	227.68

8. SUMMARY

The SPDE Tool is developed as a preliminary tool to determine the sensors required to answer planetary science mission questions. Given a planetary body and a description of planetary science objectives to be accomplished, the tool will determine the sensors needed to return the results. SPDE selects the sensor components based on the input criteria and the planetary environmental properties. Selection of the final sensor components are then based on additional operational parameters that vary for each different sensor component. Databases for each type of sensor are based on commercially available sensors. The goal of this is to reduce the amount of time spent performing trades studies to determine the correct sensor to use. Use of existing commercially developed products and flight rated hardware reduces time and cost of new space missions by having to develop new custom hardware components for each mission.

A benchmark case for the sensor design algorithms was performed on the Huygens probe mission to Titan. Science objectives for each sensor package were broken down into the different types of sensor data that was to be provided. The requirements for the different sensors were input into the SPDE input file along with the sensor package weight and power limits. Evaluating each sensor package resulted in selection of the Huygens hardware for known flight components. For sensors where the commercial component was unknown, similar performing sensors were chosen based on operational range, environmental properties and the other sensor requirements input into the SPDE program file. The resulting design configurations agree within a reasonable margin to the sensor package mass and power requirements.

The SPDE tool also aids in mission design. Based on the knowledge of the planetary science mission a preliminary payload mass budget can be determined. With this knowledge the associated spacecraft hardware can be determined required to support the mission. The size of the spacecraft will determine the required size of the launch vehicle and the operating capabilities it will need to have to send the probe to its target. This information can then be used to determine the operating timeline for the mission.

The addition of the PrISM spacecraft modeling tool to the SPDE design evaluation links together the basic elements of a mission design tool. Mission planning can begin with the basic concept. With the SPDE tool, a mission science payload package is designed. Linked together with the PrISM design tool the SPDE science package can be processed into a overall mission design with mass, volume, and power budgets for each of the spacecraft subsystems and detailed information regarding the design of each of the systems.

Each of the tools can be executed and operated independently to perform their separate design studies. Alternatively the tools can be coupled together to design the mission profile from the initial concept through preliminary spacecraft design. The tools presented here can be continuously updated throughout the development phase to refine the concept.

9. FUTURE WORK

A design framework has been established here for a tool to determine the optimal sensor configurations based on the mission science requirements. As new planetary missions are executed, sensor components within the databases can be updated, and selection algorithms refined. Additional selection criteria can be made to the tool for system level parameters and account for interactions between the sensors and the spacecraft systems.

Development of custom sensor configurations today will lead to common components in the future. The

science and technology for these new sensor designs can be built into the SPDE Program and expanded as new methods are found to determine answers to new scientific questions.

Within the PrISM tool, the design subroutines can be expanded to model additional aspects of the spacecraft's design. Subroutines can be incorporated into the framework established here to design additional aspects of the spacecraft's systems. Databases within each module can be expanded to include detailed calibration data based on different mission classes. Mass, power and volume relations vary depending on the intent of the vehicle's mission. Fine tuning of scaling parameters will allow the design tool to more accurately handle different vehicle profiles. The PrISM tool can also handle simple initial parametric trade space studies to generate initial design concepts and begin designing more complex systems as the mission profile and components get refined.

Use of the two design tools described here in combination, SPDE for mission payload design and PrISM for spacecraft design, allows for quick evaluation of mission scenarios. Concepts for planetary probe missions can be quickly evaluated to determine the scale of the mission and the design.

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