Space System Architecture of India's ADITYA-L1 Mission to Study the Sun

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ABSTRACT

The Sun, our nearest star, is an excellent plasma laboratory where the plasma behaves as a fluid near the solar corona whereas the solar wind plasma near the Earth can be considered as a particle. The outer layers of the Sun's atmosphere extending to thousands of km above the disc (photosphere) are known as solar corona. It has a temperature of more than a million degrees Kelvin while the photosphere temperature is around 6,000 K. How the solar corona gets heated to such a high temperature is still an unsolved mystery in solar physics.

Aditya-L1 spacecraft is a dedicated space science mission of the Indian Space Research Organization (ISRO) to study the Sun from the halo orbit around the Lagrangian point (L1) of the Sun-Earth system. The orbit around L1 provides continuous solar observations without any eclipse/occultation and is an excellent outpost outside Earth's magnetic field to make in-situ measurements of incoming charged particles. Aditya-L1 Mission is planned for a launch by a PSLV-XL rocket into an elliptical Earth Parking Orbit of 245 km by 21,000 km in 2020. The onboard satellite propulsion will be utilized to raise the orbit, transfer to the L1 point and maintain the L1 halo orbit. The transfer period is planned to be around 100 days and the mission has a nominal lifetime of five years.

Aditya-L1 is a 1500 kg-class satellite carrying seven payloads. The payloads cover the Sun's photosphere (ultraviolet (UV) and soft and hard X-rays), chromosphere (UV) and corona (visible and NIR). The main science payloads are the Visible Emission Line Coronagraph (VELC), Solar Ultraviolet Imaging Telescope (SUIT), Solar Low Energy X-ray Spectrometer (SoLEXS), High Energy L1 Orbiting X-ray Spectrometer (HEL1OS), and three in-situ instruments, Magnetometer (MAG), Aditya Solar wind Particle Experiment (ASPEX) and Plasma Analyzer Package for Aditya (PAPA).

This paper presents an overview of the space system architecture and science objectives of India's Aditya-L1 Mission to study the photosphere, chromosphere and corona of the Sun, detailing spacecraft architecture, science instruments, launch vehicle, mission design and ground segment through value-driven design model and tradespace exploration methods.

I. INTRODUCTION

India began space activities in 1962 with the setting up of Indian National Committee for Space Research (INCOSPAR). The Indian Space Research Organization (ISRO) was established in November 1969. The Space Commission and the Department of Space (DOS) were formed in June 1972 by the Government of India. Department of Space (DOS) has the primary responsibility of promoting the development of space science, technology and applications towards achieving self-reliance and facilitating in all round development of the nation. ISRO is responsible for the design and development of launch vehicles for access to space and orbiting Indian National Satellite (INSAT) program for telecommunication, Indian Remote Sensing (IRS) satellite program for management of natural resources, Indian Regional Navigation Satellite System (IRNSS) and space science missions. The Advisory Committee for Space science (ADCOS) formulates the vision and reviews mission plans and science payloads for astronomy and planetary exploration.[1]

India's first mission to the moon, Chandrayaan-1 spacecraft carrying both Indian and international science payloads was successfully launched on October 22, 2008 by the PSLV C-11 Rocket. NASA's Moon Mineralogy Mapper (M3) instrument discovered surficial water in the Moon. ISRO's Altitudinal Composition Explorer (CHACE) mass spectrometer payload onboard the Moon Impact Probe (MIP) detected water in the vapor phase. India's first planetary mission to Mars, Mars Orbiter Mission ("Mangalyaan") was launched on November 05, 2013 by a PSLV Rocket and successfully entered an elliptical orbit around Mars on September 24, 2014. Mars Orbiter through its five scientific payloads continues to provide valuable data of Mars surface and its atmosphere. ASTROSAT satellite, India's first dedicated astronomy satellite was successfully launched on September 28, 2015. ASTROSAT enables simultaneous multi-wavelength (Ultraviolet to X-Ray) observations to study Stars and Galaxies.[2] India's second mission to the Moon, Chandrayaan-2 spacecraft consisting of an Orbiter and a Lander module named '*Vikram*' with a Rover is slated to be launched in early 2019 by a GSLV MK-3 Rocket.

II. MULTI-ATTRIBUTE TRADESPACE EXPLORATION (MATE) METHOD

The development of a space system typically requires a large amount of resources and political capital motivated by a need to meet the requirements of many potential stakeholders. The multiplicity of perspectives of the many stakeholders for such systems make it an intricate design problem in defining the meaning of “benefit” and “cost” depending on the stakeholder considered. Tradespace exploration (TSE) techniques have been typically used to generate large datasets to gain insights into design-value, cost-benefit tradeoffs for complex aerospace systems.[3]

Tradespace exploration (TSE) is a model-based investigation that allows the designer and other decision makers to explore the design space taking into consideration a set of strongly interdependent variables and optimize for more than one metric/ objective. The most common objectives are maximizing performance and minimizing cost. Tradespace exploration paradigm is fundamentally based on decision analysis, which is domain independent and hence the approach should apply to non-aerospace domains such as data-driven healthcare and financial modeling. Tradespace exploration analyses can display *correlations* between various elements of the tradespace. *Causation* can only be determined by subject matter experts and system architects and modelers, who should be part of the TSE.[4]

The aim of a well-developed tradespace exploration (TSE) is an understanding of not only good designs, but also the trades between them, their strengths and weaknesses, the sensitivities involved that can be exploited to find improved designs, and a sense of a selected design’s robustness.[5] This overall knowledge aided by TSE visualization tools is an excellent system design and management technique for architects, designers and decision makers.

In the past decade, researchers have coupled tradespace design exploration with multi-attribute utility theory (MAUT) where system utility, which is computed as a function of system performance attributes, is used as a surrogate for value. This is particularly useful for non-commercial systems such as space science missions and for systems where overall value is multi-dimensional such as measuring health outcomes where it is difficult to monetize value delivery through metrics such as net present value (NPV). Research in this area has given rise to methods such as multi-attribute tradespace exploration (MATE).[6]

Multi-Attribute Tradespace Exploration (MATE) is a conceptual design method developed at MIT that combines MAUT and TSE. MATE compares large numbers of candidate system designs using experimental designs to enumerate vectors of design variables that are evaluated by system performance models. The performance attributes for each design are then evaluated using a valuation metric, typically a multi-attribute utility (MAU) function ranging from 0 to 1, with 0 defined as minimally acceptable and 1 as the point where no further benefit is gained. MAU is plotted against their respective costs to identify the frontier of Pareto optimal solutions. Comparing alternatives in this way helps mitigate potential biases or premature fixation on a single-point design.[7]

The Multi-Attribute Tradespace Exploration (MATE) process consists of the following steps:

1) Identify the stakeholders
2) Define a mission objective/ concept
3) Create a list of attributes
4) Determine design variables and map them to attributes
5) Create a model that gives rise to utility curves
6) Evaluate architecture for further study

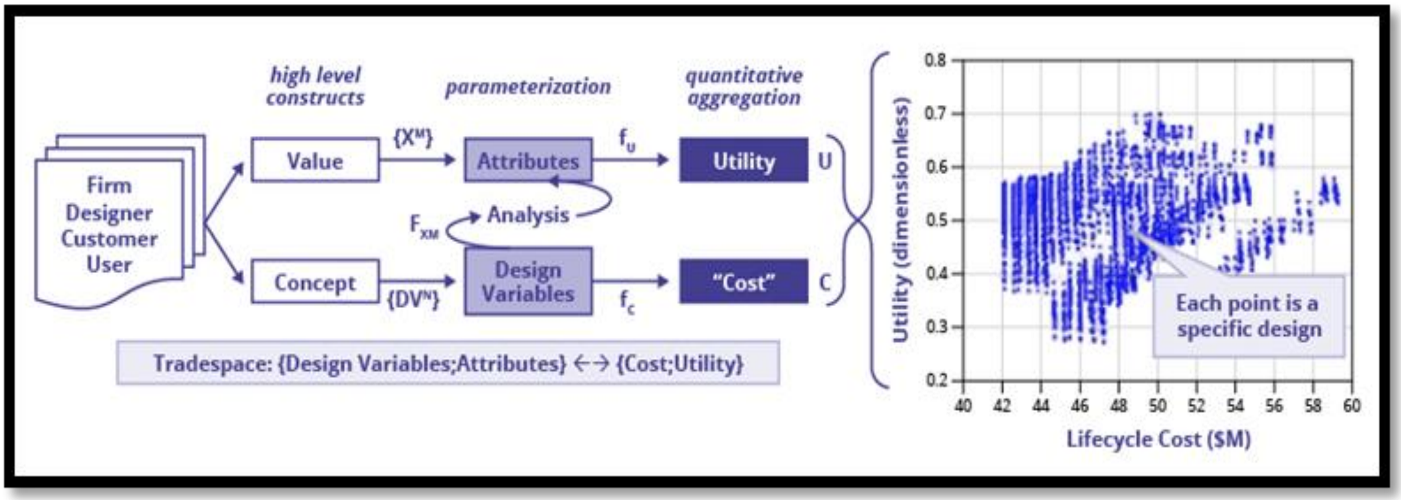


Fig 1: Multi-Attribute Tradespace Exploration (MATE) (Source: MIT SEAri)

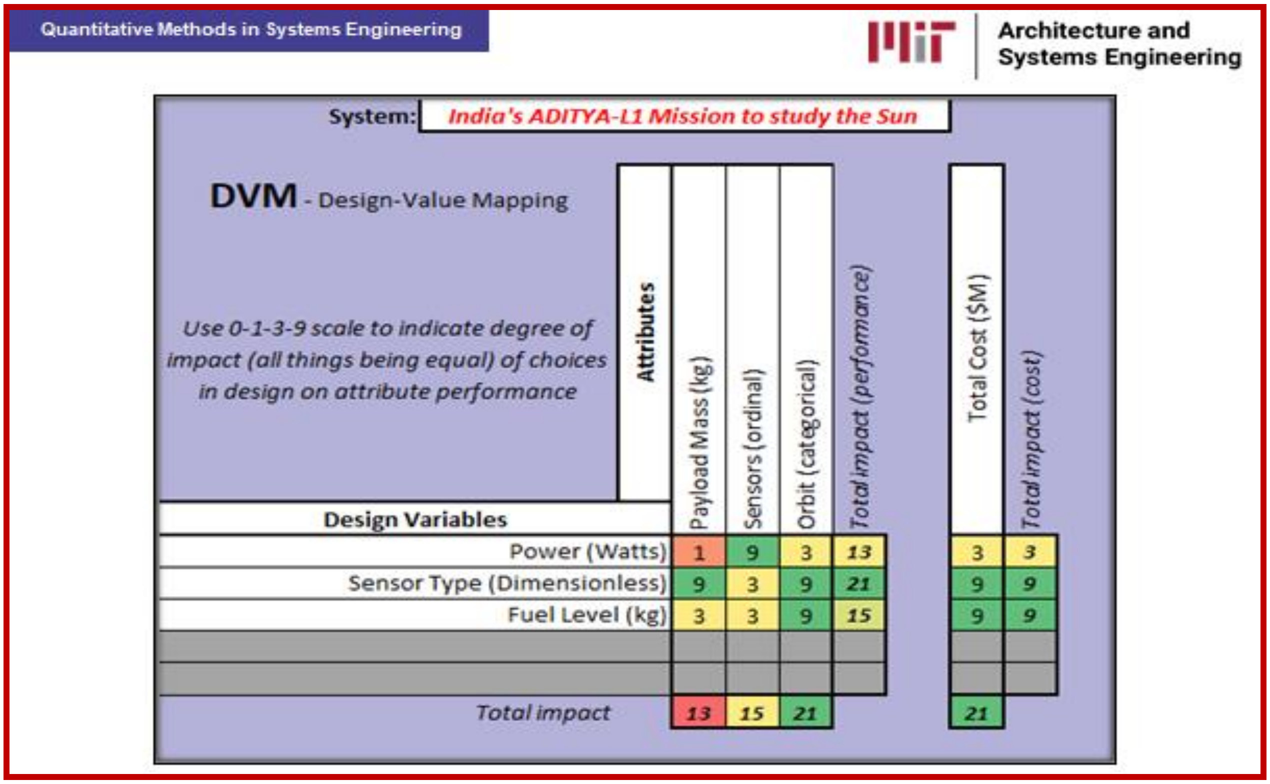
III. DESIGN VALUE MAPPING (DVM) FOR ADITYA-L1 MISSION

The creation of “value” is a well-established goal in any project endeavor. From an engineering perspective, the concept of creating value goes hand-in hand with fundamental goals in system and product design (meeting customer or user needs), as well as systems engineering (capturing requirements and developing systems that meet them). However, part of the lack of clarity is due to the inherent ambiguity of the term “value”. In the context of a space science mission system design, value can be defined as a balance of benefit at cost (worth), satisfaction or usefulness (utility), and priority (importance).[8]

In a value-centric design methodology, multiple attribute utility theory (MAUT) is often used instead because of its ability to rank systems based on their aggregate benefit (called MAU), relative to a pre-determined set of attributes, which each characterize a desirable (or sometimes an undesirable) aspect of a system. Subsequently, MAUT allows for the quantitative aggregation of monetary, but also non-monetary, stakeholder preferences for, and hence stakeholder perceived value of, a given system. MAUT quantifies a value proposition in terms of the ordered pair of MAU and lifecycle cost, but both value propositions are derived from an identical set of attributes (benefits). For this research, an attribute is a characteristic of a spacecraft (system) assumed to embody objectives of a system that are useful/desirable to the stakeholder(s) of interest and adhere to the five properties of an attribute set established by Keeney and Raiffa: *complete*, *operational*, *decomposable*, *non-redundant*, and *minimal*.[9] Design variables are factors under the control of the designer (decision maker) that can be parameterized to represent each design concept.

The Design Value Mapping (DVM) method provides a way to assess the design concepts’ ability to fulfill stakeholder needs, allowing decision makers to focus on the key utility drivers and to identify value expectations that are potentially difficult to drive. The relationships between each design variable and attribute pair can be represented using a DVM matrix. A non-linear scale of 0,1,3 and 9 is used to represent either no, weak, medium and strong relationship. The sum of the cells down each column represents whether an attribute is being weakly or strongly driven by the current set of design variables. Similarly, cells are summed up across each row to indicate whether the design variable is a strong or weak driver of the value attributes. DVM also provides some insights on the important interactions that should be captured in the model for tradespace generation by alignment between value-space that are concept-neutral evaluation criteria and design-space.[10]

For India’s first space mission to study the Sun, ADITYA-L1 spacecraft, three attributes and three design variables are selected based on stakeholder value preferences gleaned from mission proposal documents for tradespace exploration. The DVM matrix in *Fig. 1* provides the impact of each design variable on the three selected output attributes and on total cost.



Quantitative Methods in Systems Engineering

Architecture and Systems Engineering

System: *India's ADITYA-L1 Mission to study the Sun*

DVM - Design-Value Mapping

Use 0-1-3-9 scale to indicate degree of impact (all things being equal) of choices in design on attribute performance

Design Variables \ **Attributes**	Payload Mass (kg)	Sensors (ordinal)	Orbit (categorical)	*Total impact (performance)*	Total Cost ($M)	*Total impact (cost)*
Power (Watts)	1	9	3	*13*	3	*3*
Sensor Type (Dimensionless)	9	3	9	*21*	9	*9*
Fuel Level (kg)	3	3	9	*15*	9	*9*
Total impact	*13*	*15*	*21*		*21*	

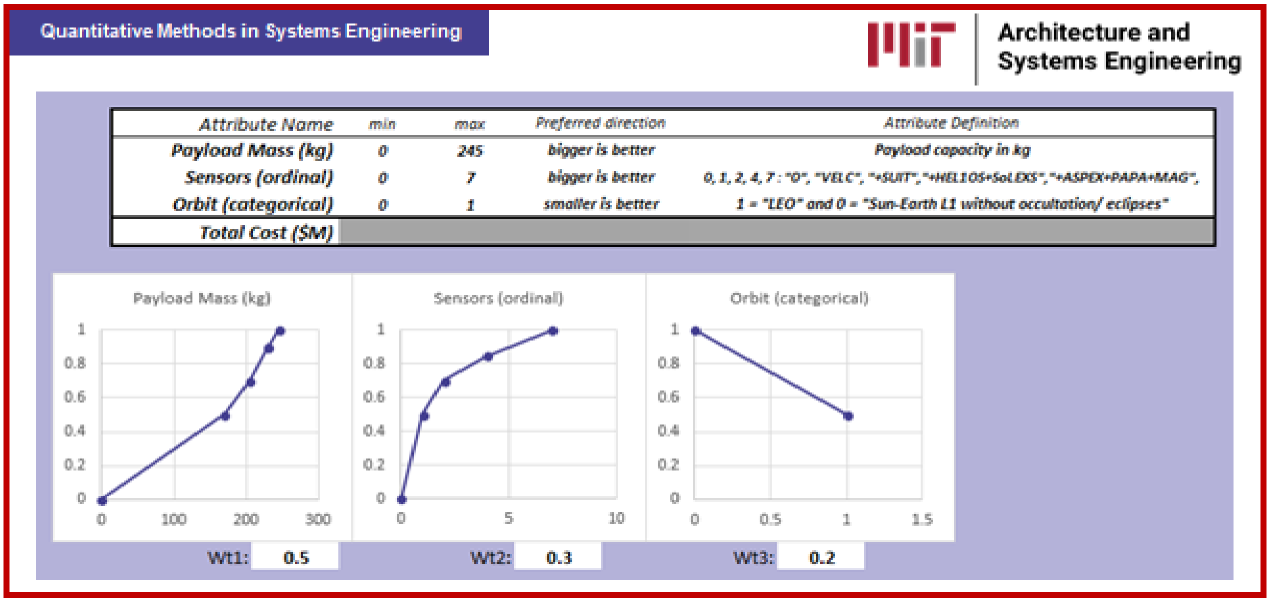
Source: *Author’s Value-Driven Tradespace Exploration Design Project for MIT Architecture & Systems Engineering Certificate Program*

IV. TRADESPACE EXPLORATION FOR ADITYA-L1 MISSION

Tradespace exploration (TSE) is a modern engineering practice that explores a design space by enumerating and evaluating many potential designs, including the Pareto efficient front that represents the set of non-dominated designs across the considered objectives (often, cost and benefit value metrics). The Pareto front are determined algorithmically and involves determining solutions that are equal to or better than other solutions across their objectives. Tradespace exploration has been found to be particularly useful for the design of complex engineering systems with multiple dimensions of benefit. Tradespace exploration is an attractive technique for problems in which there are multiple decision makers or stakeholders with different value propositions or “preferences” defining their utility functions.[11]

A computational model is used to calculate the attribute values for some or all the possible designs in the design vector, their single (SAU) and multi-attribute utilities (MAU) for one or more stakeholders and their costs. A value model defines the mapping of performance attributes to a perceived value (U) of a given system. The value (U) is computed using a multi-attribute utility (MAU) function. Each MAU function may be comprised of several single-attribute utility (SAU) functions that correspond to the stakeholder’s description of preferences for each performance attribute. Each SAU function defines a mapping from the performance attribute level to a SAU quantity. The linear weighted sum of the SAU quantities is the MAU or perceived value (U) of the system.[12]

For the ADITYA-L1 Mission tradespace exploration design study, three space system performance attributes are considered: Payload Mass, Sensors and Orbit (LEO or L1). Payload Mass is the total mass of the payloads in kg, sensors are the seven payloads in five ordinal options: zero, VELC (Visible Emission Line Coronagraph), +SUIT (Solar Ultraviolet Imaging Telescope), +HEL1OS+SoLEXS (High Energy L1 Orbiting Spectrometer + Solar Low Energy X-ray Spectrometer), +ASPEX+PAPA+MAG (+ Aditya Solar wind Particle EXperiment + Plasma Analyzer Package for Aditya + Magnetometer) and the categorical Orbit options of either Low Earth Orbit (LEO) or Sun-Earth Lagrangian Point (L1) halo orbit. The SAU values and their weights in calculating the MAU are given below.



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Attribute Name	min	max	Preferred direction	Attribute Definition
Payload Mass (kg)	0	245	bigger is better	Payload capacity in kg
Sensors (ordinal)	0	7	bigger is better	0, 1, 2, 4, 7 : "0", "VELC", "+SUIT","+HEL1OS+SoLEXS","+ASPEX+PAPA+MAG",
Orbit (categorical)	0	1	smaller is better	1 = "LEO" and 0 = "Sun-Earth L1 without occultation/ eclipses"
Total Cost ($M)				

Wt1: 0.5

Wt2: 0.3

Wt3: 0.2

Source: *Author’s Value-Driven Tradespace Exploration Design Project for MIT Architecture & Systems Engineering Certificate Program*

The primary science instrument of the ADITYA-L1 Spacecraft, Visible Emission Line Coronagraph (VELC) sensor alone has a payload mass of 170 kg, followed by Solar UV Imaging Telescope (SUIT) with a mass of 35 kg. The combined mass of other 5 sensors are only 40 kg. This explains the steeper slope of SAU curve for Payload Mass attribute, after the first value (primary sensor, VELC). At the best performance attribute values, the SAUs contribute fully to the MAU. The Orbit attribute has a SAU of 0.5 even at its worst value ("1" = LEO). The maximum MAU achievable at the sub-optimal LEO orbit is only 0.8 since in-situ measurement sensors (ASPEX+PAPA+MAG) would be useless under the influence of Earth's magnetic field. The utility weights of the three performance attributes are Payload Mass (0.5), Sensors (0.3) and Orbit (0.2). The MAU is the linear weighted sum of the three SAU performance attributes utility values. For example, ISRO’s originally envisioned ADITYA Mission design with a single payload (VELC) stationed at LEO would have provided a MAU of **0.5** (= 0.5*0.5+0.3*.5+0.2*0.5) at full required power capacity in the tradespace exploration analysis.

The tradespace exploration (TSE) design variables for the ADITYA-L1 Mission, Power (Watts), Sensor Type and Fuel Level (kg) are selected based on their strong relationship with the three performance attributes, Payload Mass, Sensors and Orbit and on total cost as shown in the Design Value Mapping (DVM) matrix. The design variable Power has three factor levels: 500W, 1000W and 1500W. The Sensor Type has four factor levels: 1,2,3,4 and the design variable Fuel Level varies in level from 250 kg to 850 kg.

The tradespace exploration (TSE) model that gives rise to utility curves has two types of design vector inputs; variables that are enumerated and a set of constants as input to the model as shown in *Fig. 2*. The tradespace design concepts with the Pareto front from the generated data can provide multi-dimensional insights about the relationship between what is asked for (needs) and what is possible (alternative designs). Each design concept can be represented by parameterization of design vectors using the generated tradespace data.[13]

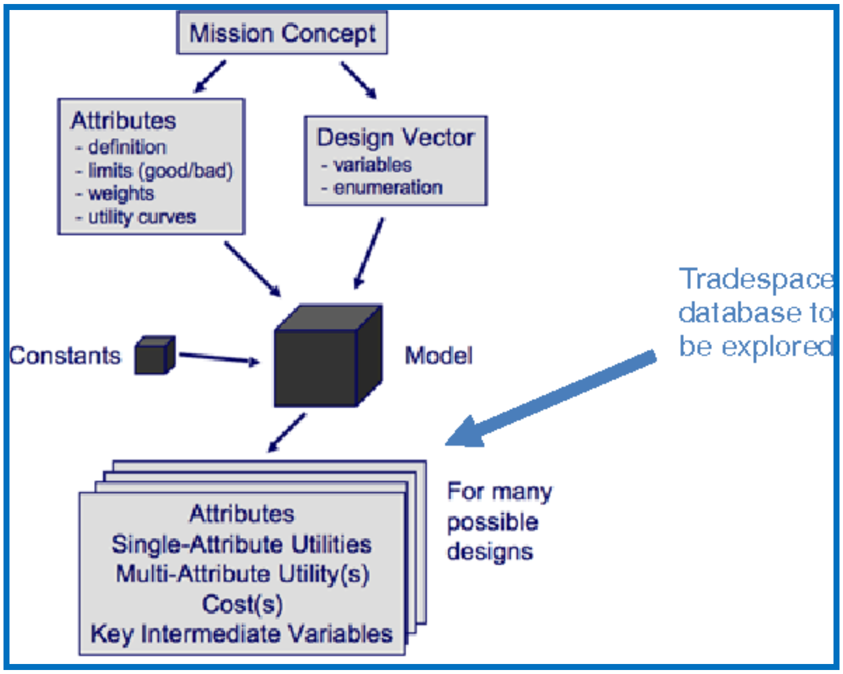
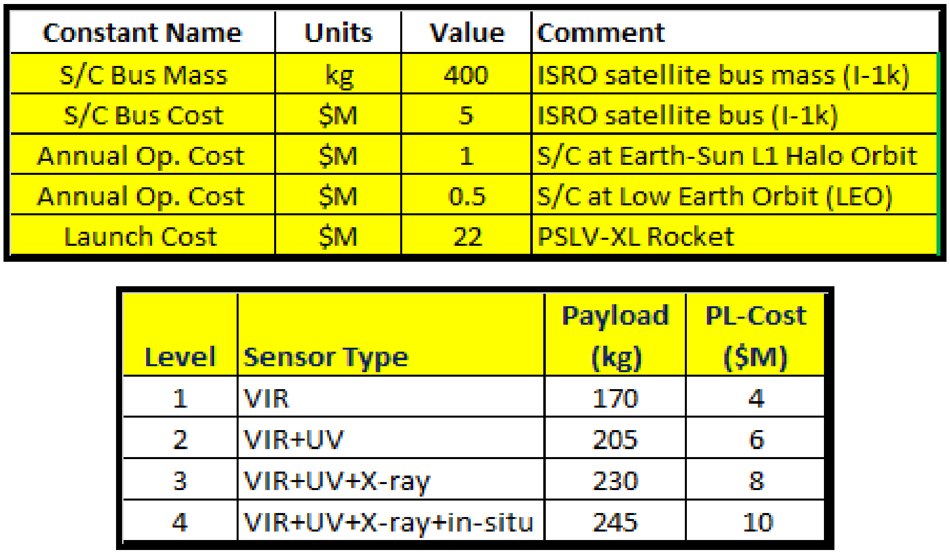


Fig 2: Generating Tradespace Data (Credit: Adam M. Ross, et.al)

The values for the constants used as inputs to the tradespace exploration (TSE) model are provided below in *Fig. 3*:



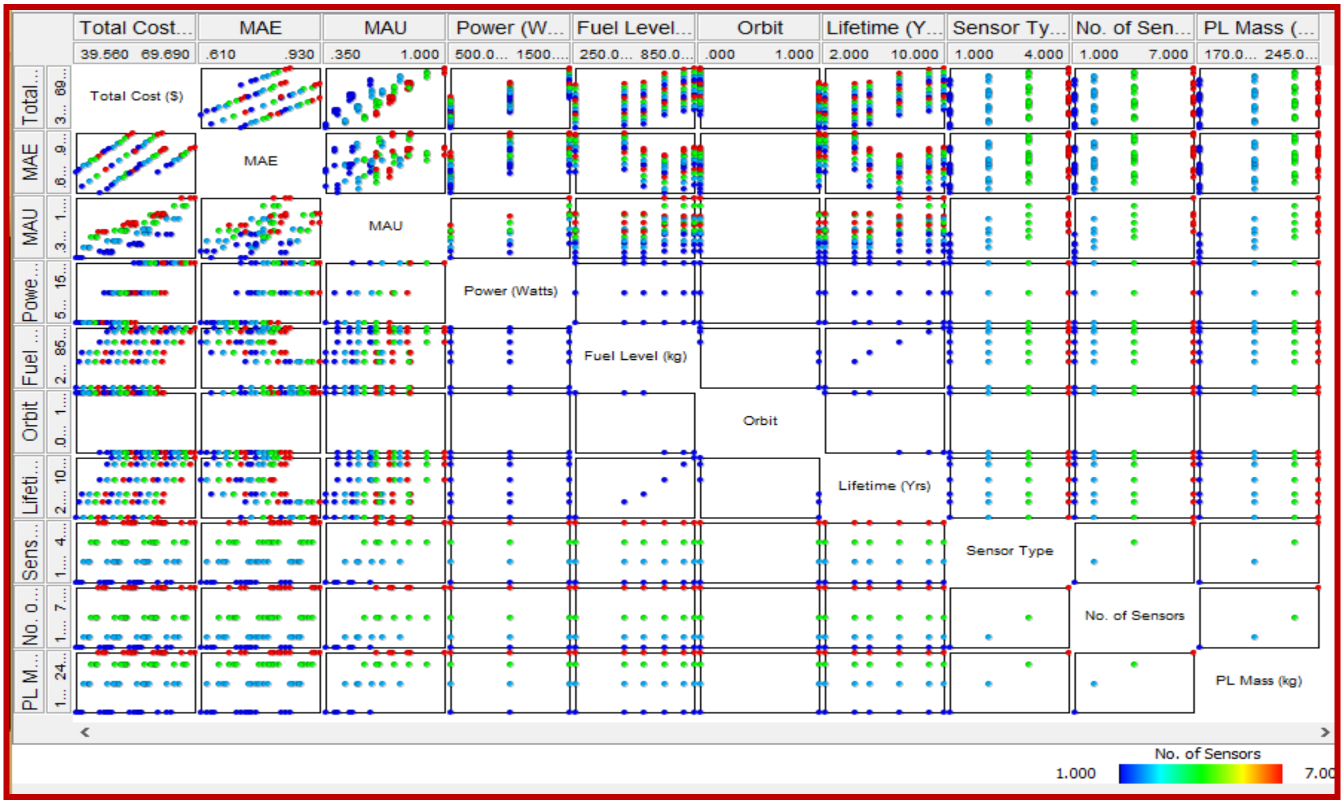
Constant Name	Units	Value	Comment
S/C Bus Mass	kg	400	ISRO satellite bus mass (I-1k)
S/C Bus Cost	$M	5	ISRO satellite bus (I-1k)
Annual Op. Cost	$M	1	S/C at Earth-Sun L1 Halo Orbit
Annual Op. Cost	$M	0.5	S/C at Low Earth Orbit (LEO)
Launch Cost	$M	22	PSLV-XL Rocket

Level	Sensor Type	Payload (kg)	PL-Cost ($M)
1	VIR	170	4
2	VIR+UV	205	6
3	VIR+UV+X-ray	230	8
4	VIR+UV+X-ray+in-situ	245	10

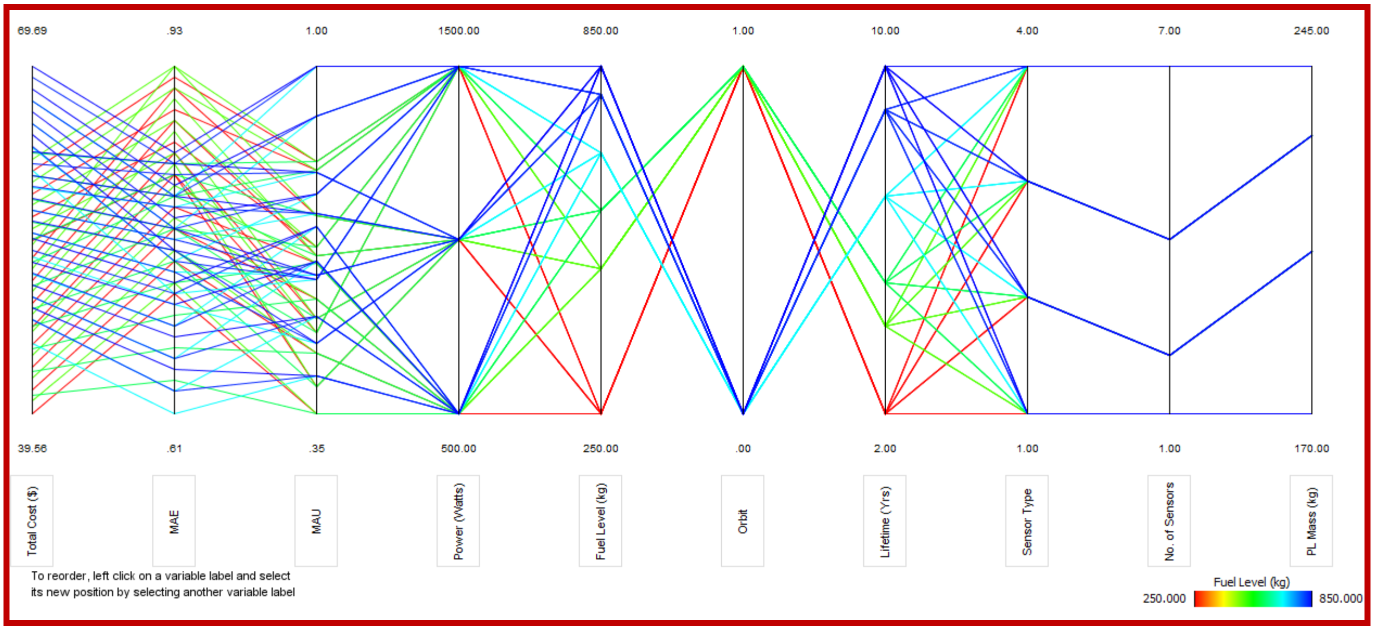
Fig 3: ADITYA-L1 TSE Model values for constants (Source: ISRO, Author's research)

The *Multi-Attribute Tradespace Generation, Exploration and Analysis Tool* from MIT[14] was utilized for the ADITYA-L1 Mission tradespace exploration (TSE) data generation, representation and design concepts evaluation. The *ARL Trade Space Visualizer (ATSV) software application tool* from Penn State University[15] was utilized for visualizing the multi-dimensional tradespace data to identify relationships between different design variables, dynamically applying constraints and preferences to provide the decision maker with the intuition needed to make best decision.[16]

A scatter matrix plot below provides the relationship among the different design variables, attributes and cost functions (Total Cost ($) and Multi-Attribute Expense (MAE)) for the ADITYA-L1 Mission.

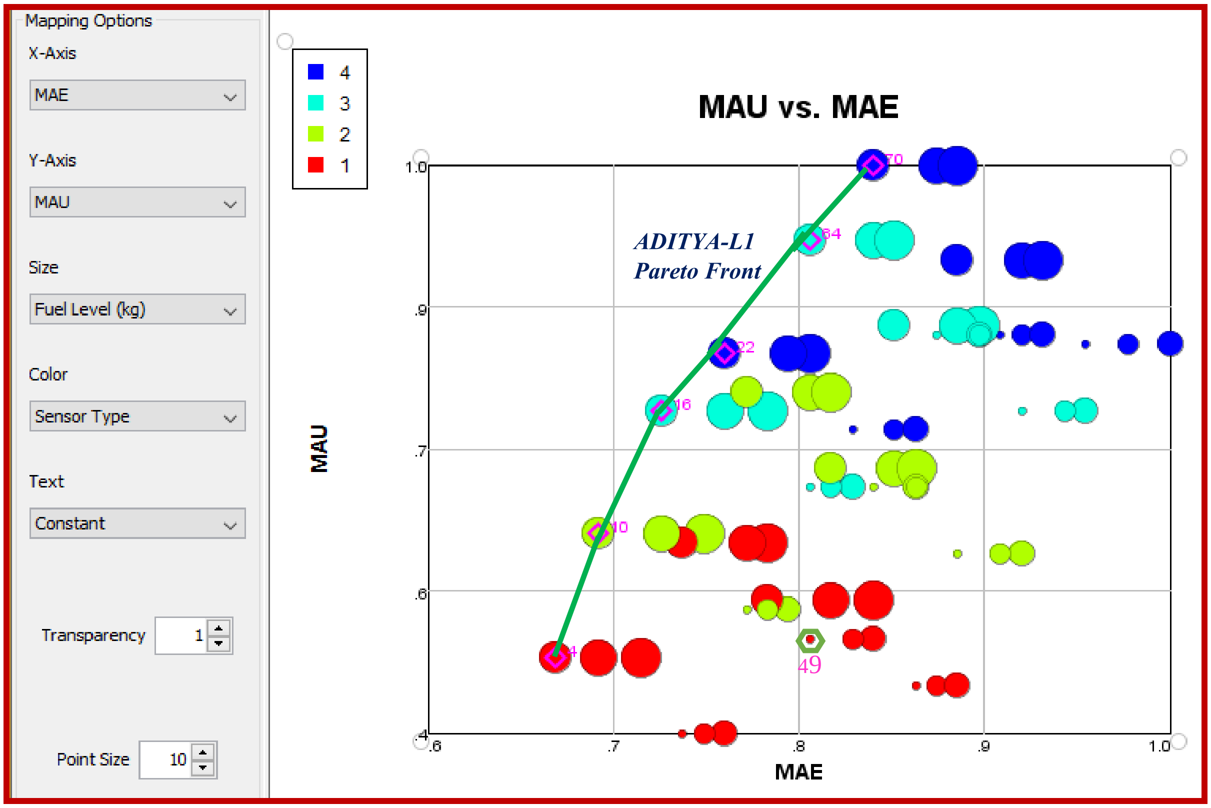


A parallel coordinates plot showing ten objectives and spacecraft Fuel Level (kg) for ADITYA-L1 Misison is shown below.



The cost attribute for the ADITYA-L1 Mission tradespace exploration is the sum of the spacecraft development cost, science payloads cost, spacecraft launch cost and annual mission operations cost for the duration of the mission. Given the complexity of a space science mission with different expectations of the stakeholders and decision-makers, a Multi-Attribute Expense (MAE) is utilized instead of the cost attribute. The MAE considers cost, schedule and other non-monetary factors that are often difficult to express in monetary values. The MAE function is formulated similar to the MAU function, where the notion of expense is akin to negative utility. Quantified on a scale of 0 to 1, an expense level of 1 denotes complete dissatisfaction and an expense level of 0 denotes minimal dissatisfaction.[17]

In the MAU vs. MAE plot shown in Fig. 4, the Pareto frontier represents the set of non-dominated 'best solution' space architecture designs in the tradespace exploration across the considered objectives. Good designs in the fuzzy Pareto front are located a 'fuzzy' distance off the Pareto front. The designs on the 'true' Pareto front have a Fuzzy Pareto Number (FPN) of zero, while a design that is 20% 'inefficient' compared to designs on the Pareto front has an FPN of 20.[18]



Mapping Options
X-Axis
MAE
Y-Axis
MAU
Size
Fuel Level (kg)
Color
Sensor Type
Text
Constant
Transparency 1
Point Size 10

Fig. 4: Multi-Attribute Utility (MAU) vs. Multi-Attribute Expense (MAE) for the ADITYA-L1 Mission TSE

The *Fig. 5* shows how the attractiveness (MAU) of each of the alternate design, those on the Pareto frontier is impacted as the weights of the three performance attributes (Payload Mass, Sensors and Orbit) for the ADITYA-L1 space science mission tradespace exploration (TSE) are swept across their range. Steep slope means high sensitivity to weight change.

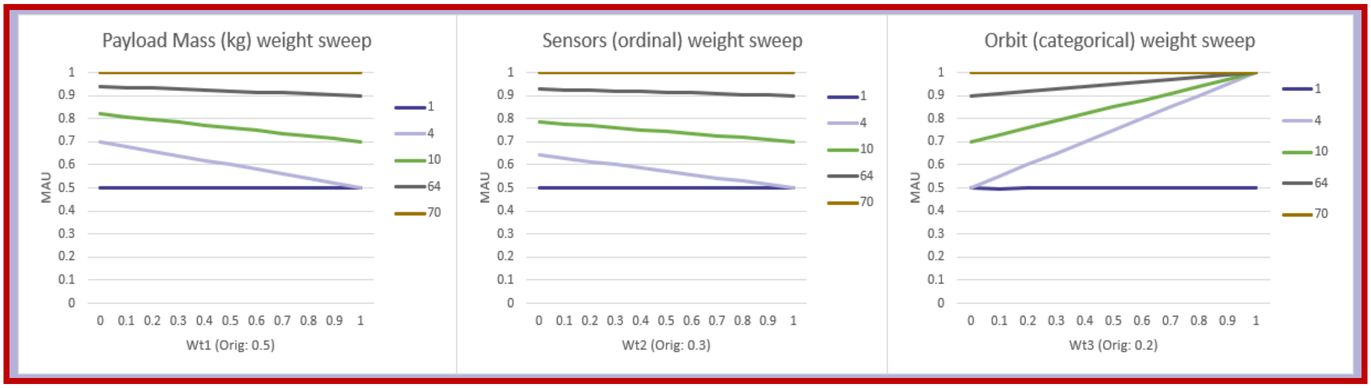


Fig 5: Sensitivity Analysis for select designs in the Pareto front for the ADITYA-L1 Mission Tradespace Exploration

V. ADITYA-L1 SPACECRAFT ARCHITECTURE

India's first space-based solar observatory was initially conceived as a 400 kg (IMS – Indian Mini Satellite) class satellite carrying one payload, a solar coronagraph to be placed in an 800 km Low Earth Orbit (LEO) for a nominal mission duration of 2-years. This original Aditya mission architecture is represented in the multi-attribute tradespace exploration (MATE) by design no. 49, with a MAU value of 0.5 and MAE value of 0.83. Based on the recommendations of Advisory Committee for Space Science (ADCOS), ISRO planned the space science mission as ADITYA-L1, the spacecraft to be placed in the Sun-Earth system Lagrangian Point 1 (L1) halo orbit with six additional science payloads on a larger satellite platform. This orbit has a major advantage of continuously viewing the Sun without any occultation/ eclipses. Also, in-situ measurement of particle and plasma environment is possible from the L1 orbit, being outside the magnetic field of Earth. The ADITYA-L1 mission tradespace exploration (TSE) Pareto front architecture designs and all within 10% of the Pareto optimality (Fuzzy Pareto Number [FPN] = 10) in the MAU vs. MAE plot visualization are all based in the L1 halo orbit as shown in *Fig. 4*.

The ADITYA-L1 spacecraft is a 1,500 kg I-1K class satellite with a power capability of about 1600 W from the two solar panels that are also used to charge a Lithium-Ion battery. The dry mass of the satellite is around 500 kg. The total mass of the seven science payloads is about 245 kg.[19]

The structure of the satellite bus is cuboidal that consists of aluminum and metallic honeycomb sandwich panels. The Attitude and Orbit Control System (AOCS) configuration consists of various types of sensors for measurement of attitude errors, control electronics and different types of actuators such as reaction wheels, magnetic torques and reaction control thrusters to impact thrust/ torque to the spacecraft in the desired direction.

The Electric Power Subsystem (EPS) is configured as a single regulated, battery charge/ discharge control and power conditioning and distribution. The power distribution scheme is based on the specific voltage and current requirements for all subsystems. The Bus Management unit (BMU) with the onboard computer (OBC) takes care of all data handling functions and interface with the star sensor and the payload. The SPS (Satellite Positioning System) provides the state vector (position, velocity and time) of the spacecraft in real-time. The TT&C transponder consists of a S-band receiver, a transmitter and the antenna. The TT&C antenna offers near omni-directional coverage to provide a reliable link during both the initial launch phase and on-orbit phase. The Solid State Recording (SSR) has the provision to support simultaneously data recording and play back.[20]

A novel automated Coronal Mass Ejection (CME) detection algorithm is implemented in onboard electronics to reduce telemetry data by 15% and enable to take even higher resolution images with limited telemetry in future. This algorithm will be the first onboard automated CME detection algorithm in space-based observations.[21]

The configuration of the ADITYA-L1 spacecraft with the seven science payloads is shown in Figure 6 below:

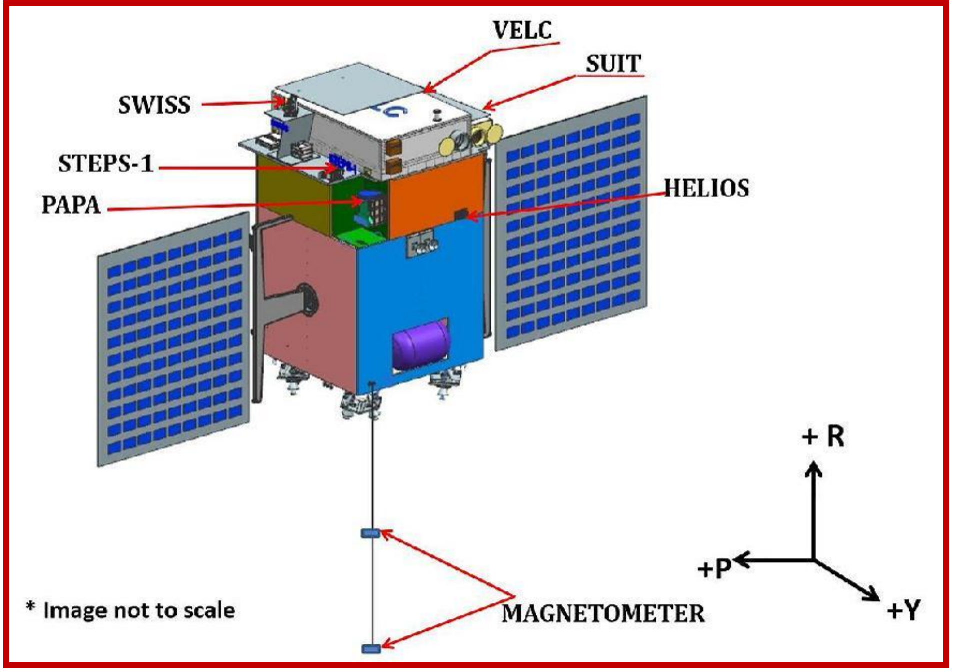


Fig 6: ADITYA-L1 Spacecraft Configuration (Credit: ISRO)

VI. ADITYA-L1 MISSION SCIENCE PAYLOADS

The ADITYA-L1 Mission is India's first ever dedicated space mission to probe the Sun, our nearest star, coinciding with the expected start of the rising phase of solar cycle 25, with a comprehensive suite of seven science payloads.

The scientific objectives of the ADITYA-L1 mission can be broadly categorized as follows:

- Studies to understand sources that heat the chromosphere and the solar corona, above the cooler photosphere.
- Sequence of processes occurring on different layers of the Sun, especially leading to phenomena in the corona.
- Origin and dynamics of solar wind, solar flares and Coronal Mass Ejections (CMEs)
- Solar spectral irradiance (UV) variations in the chromosphere.
- Estimate of coronal magnetic field from space.[22]

The science objectives of the seven science instruments onboard ADITYA-L1 spacecraft are provided in the table below:

Science Payload	**Sensor Type**	**Primary Science Objective**
1) Visible Emission Line Coronagraph (VELC)	VIR	Study the diagnostic parameters of Sun's coronal plasma like velocity, temperature and density, and perform spectroscopic studies in three wavebands. VELC has capability to observe the corona from 1.05 solar radii.
2) Solar Ultraviolet Imaging Telescope (SUIT)	UV	Understand the footprints of solar eruptive events and solar irradiance by imaging the solar photosphere, chromosphere and part of the transition region right up to 1.1 solar radii in the near-UV band.
3) Solar Low Energy X-ray Spectrometer (SoLEXS)	X-ray	Study initiation phase of the solar flares in the X-ray bands. SoLEXS will cover energy band from 1 to 30 keV with a spectral resolution of <4% (i.e. <250 eV at 6 keV).
4) High Energy L1 Orbiting X-ray Spectrometer (HEL1OS)	X-ray	Study the impulsive phase of solar flares with two different detectors (CZT and CdTe) in the high-energy X-ray spectrometer (10 to 50 keV) and identify the non-thermal energy release during flares.
5) Aditya Solar Wind Particle Experiment (ASPEX)	In-situ	Study the variation of solar wind properties as well as its distribution and spectral characteristics through two subsystems: Solar Wind Ion Spectrometer (SWIS) and Supra Thermal & Energetic Particle Spectrometer (STEPS).
6) Plasma Analyzer Package for Aditya (PAPA)	In-situ	Understand the composition of solar wind and its energy distribution by probing heliospheric ions and electrons with two sensors: SWICR and SWEEP (Ions 0.01 – 25 keV; Electrons 0.01 – 3 keV).
7) Magnetometer (MAG)	In-situ	Study the distributed magnetic conditions and extreme solar events by detecting the CME from Sun as a transient event by measuring the magnitude and nature of the interplanetary magnetic field (IMF) locally by a Fluxgate Digital Magnetometer (FGM), a dual range magnetic sensor on a 6m long boom mounted on the Sun viewing panel deck. (Range 256 – 60,000 nT).

- The *Visible Emission Line Coronagraph (VELC)* is the main science payload for the ADITYA-L1 mission. The solar coronagraph is being developed by Indian Institute of Astrophysics (IIA). The VELC has a mass of 170 kg.
- The *Solar Ultraviolet Imaging Telescope (SUIT)* is developed by the Inter-University Center for Astronomy and Astrophysics (IUCAA). The SUIT has a total mass of about 35 kg.
- The X-ray payload, *Solar Low Energy X-ray Spectrometer (SoLEXS)* is being developed by ISRO Satellite Center (ISAC) and the other X-ray payload, *High Energy L1 Orbiting X-ray Spectrometer (HEL1OS)* is being developed at ISAC and Physical Research Laboratory (PRL).
- The *Aditya Solar wind Particle Experiment (ASPEX)* instrument is being developed by PRL and has a mass of about 12.6 kg. ASPEX will complement coronagraphic observations by determining the arrival time of interplanetary CMEs at L1.
- *The Plasma Analyzer Package for Aditya (PAPA)* is being developed by Space Physics Laboratory (SPL) and Vikram Sarabhai Space Center (VSSC).
- The *Flexgate Digital Magnetometer (MAG)* is being developed by Laboratory for Electro optics Systems (LEOS) and ISAC and has a mass of about 3.3 kg. [23]

VII. ADITYA-L1 MISSION LAUNCH AND OPERATIONS

India's ADITYA-L1 Mission is expected to be launched by a four-stage Polar Satellite Launch Vehicle in the XL configuration using alternate solid and liquid stages with six strap-on motors during 2019-2020 from the Satish Dhawan Space Center (SDSC) in Sriharikota Island located in the state of Andhra Pradesh. The PSLV-XL Rocket will place the spacecraft in an elliptical Earth parking orbit of 245 km x 21,000 km. The orbit of the spacecraft will be gradually raised by a series of Earth orbit raising maneuvers. The spacecraft will leave the Earth's Sphere of Influence (SOI) at 918,317 km from the surface of the Earth and inserted around Sun-Earth Lagrangian Point One (L1) about 1.5 million km from Earth in about 100 days from launch. The ADITYA-L1 spacecraft will be placed in the L1 halo orbit with parameters of *AX=208951 km, AY=670024 km and AZ=120000 km*, where X-Y is ecliptic plane and Z axis is perpendicular to the ecliptic plane. The ADITYA-L1 spacecraft will have an orbital period of 177.8 days in the L1 halo orbit.[24]

The ADITYA-L1 spacecraft with its seven payloads cover the Sun's photosphere (ultraviolet (UV) and soft and hard X-rays), chromosphere (UV) and corona (visible and NIR). In addition, particle payloads will study the particle flux emanating from the Sun and reaching the L1 orbit, while the magnetometer payload will measure the variation in magnetic field strength at the halo orbit around L1.

The tradespace exploration (TSE) paradigm for the ADITYA-L1 Mission consists of three design variables. The three design variables (DV = Power, Sensor Type and Fuel Level) influence the three performance attributes (Payload Mass, Sensors and Orbit) along with the total cost.

- Design Variable (DV1), *Power (W),* is enumerated with three levels of 500, 1000 and 1500 that provide the payloads with a source of power and effect the simultaneous operations of the science instruments.
- Design variable (DV2), *Sensor Type*, is enumerated in four levels: VIR, VIR+UV, VIR+UV+X-ray and VIR+UV+X-ray+In-situ instruments.
- Design Variable (DV3), *Fuel Level (250 – 850 kg),* range specifies the mission lifetime in years from a minimum lifetime of two years to nominal life of five years but can be extended up to ten years.

The ADITYA-L1 Mission ground segment consists of the following four main entities:

- Satellite Control Center (SCC) at ISRO Telemetry Tracking and Command Network (ISTRAC)
- Indian Deep Space Network (ISDN),
- Indian Space Science Data Centre (ISSDC), and
- Payload Operations Centre (POC).

ISRO Satellite Control Center (SCC) is located at Peenya campus of ISTRAC near Bengaluru in the state of Karnataka. ISTRAC provides Telemetry, Tracking and Command (TTC) services from launch vehicle lift-off till injection of satellite into orbit. ISTRAC has established a network of ground stations at Bengaluru, Lucknow, Mauritius, Sriharikota, Port Blair, Thiruvananthapuram, and Brunei, Biak (Indonesia). For the initial phase operations, the network will be augmented with additional network stations from other agencies.

Indian Deep Space Network (IDSN) consisting of 11-m, 18-m and 32-m antennae were established at the IDSN campus in Byalalu near Bangalore as part of the Chandrayaan-1 mission ground segment in 2008. The IDSN station will receive the ADITYA-L1spacecraft health data as well as the payload data.[25]

Indian Space Science Data Center (ISSDC) is a facility established by ISRO for deep space missions, as the primary data center for the payload data archives of Indian Space Science Missions. This data center, located at the Indian Deep Space Network (IDSN) campus in Bengaluru, is responsible for the ingestion, archive, and dissemination of the payload data and related ancillary data for the Space Science missions. ISSDC interfaces with Mission Operations Complex (MOX) through dedicated communication links, Data reception centers, Payload designers, Payload operations centers, Principal investigators, Mission software developers and Science data users.

Payload Operation Centres (POCs) focus on the higher levels of science data processing, planning of payload operations, performance assessment of the payload and payload calibration. These centers are co-located with the institutions/laboratories of the Instrument designers, Principal Investigators and will be processing and analyzing data from a specific payload. POCs will pull relevant payload (level 0 and level 1) and ancillary data sets from the ISSDC dissemination server and process the data to generate higher level products. These products will be archived in ISSDC after qualification.

VIII. FINDINGS AND CONCLUSION

- Established in 1969, the Indian Space Research Organization (ISRO) implements the vision of the Department of Space (DOS) through the following programs: (a) Earth Observation – Indian Remote Sensing (IRS) Satellites, (b) Telecommunications & Weather – Indian National Satellites (INSAT), (c) Navigation – Indian Regional Navigational Satellite System (IRNSS) and (d) Planetary Exploration & Space Science Missions.

- The success of India's first dedicated space exploration mission to Moon, Chandrayaan-1 launched in 2008 that carried five Indian and six international scientific instruments heralded a new era in with dedicated Planetary Exploration and Space Science missions as key components of the Indian Space Program. NASA and ISRO instruments both collectively discovered unambiguous signatures for the distribution of water in solid and gaseous phases in Earth's Moon, linked to abundance of surficial OH/ H_2O in the lunar highlands and parts of the mare regions.

- India's first interplanetary mission to the Red Planet, Mars Orbiter Mission ("*Mangalyaan*") was launched on November 5th, 2013 by a PSLV-XL Rocket. MOM is successfully orbiting Mars since 24 September 2014 carrying out scientific study of Martian atmosphere and its surface through five remote sensing instruments.

- ASTROSAT, India's first dedicated space observatory was launched into a 650 km near Earth, equatorial orbit on September 28th, 2015. It is currently performing multi-wavelength observations covering spectral bands from radio, optical, IR, UV and X-ray wavelengths. Chandrayaan-2 Spacecraft consisting of an Orbiter with a Lander module carrying a small Rover is slated for launch during early 2019 by a GSLV MK-3 Rocket.

- ADITYA-L1 Mission is India's first dedicated space solar observatory with seven science payloads to be placed in the Sun-Earth Lagrangian Point (L1) halo orbit. The primary payload is a Solar Coronagraph (VIR) with additional instruments to collect data on the Sun's photosphere (ultraviolet (UV) and soft and hard X-rays), chromosphere (UV) and three in-situ instruments. Aditya mission was originally conceived as a single payload (Coronagraph) small spacecraft in the Low Earth Orbit. ADITYA-L1 Mission is planned for a launch during 2019-20.

- Tradespace Exploration (TSE), a model-based investigation of many design alternatives is explored in this research project paper to evaluate various space system architecture for the ADITYA-L1 Mission. A Design Value Mapping (DVM) was performed to identify the three important performance attributes (Payloads, Sensors and Orbit) for the stakeholders along with total cost, the dependent top three design variables (Payload Mass, Sensor type and Fuel Level) and the relationships between each design variable and attribute pair for gaining insights on interactions among the value-space and design-space in the tradespace exploration.

- A detailed tradespace exploration (TSE) analysis of ADITYA-L1 Mission space architecture designs was carried out utilizing the *Multi-Attribute Tradespace Generation, Exploration and Analysis Tool* developed at MIT Systems Engineering Advancement Research Initiative (SEAri). The Pareto Front that represents the set of non-dominated designs across the considered objectives (MAU vs. MAE metrics) are identified as the 'best' solutions in the tradespace.

- The *ARL Trade Space Visualizer (ATSV) software application tool* from Penn State University was employed for visualizing the multi-dimensional tradespace datasets. Several 'good' designs in the fuzzy Pareto Front that are located a "fuzzy" distance off the Pareto front were also identified. All the designs within a Fuzzy Pareto Number (FPN) of 10, are for designs where the spacecraft is placed in the Sun-Earth Lagrangian Point One (L1) halo orbit.

- The ADITYA-L1 Mission tradespace exploration (TSE) analysis and visualization of data can be utilized by decision makers to maximize the return (MAU vs. MAE) for various combinations of available Power (W) and Fuel Level (kg) during the mission. The sensitivity analysis on the Pareto Front designs provide a starting point for developing a plan and pursuit of decisions that are more robust for anticipated variations.

- A future research for the ADITYA-L1 Mission Tradespace Exploration (TSE) project could be to perform an *Epoch Era Analysis* (EEA) to evaluate the outcome of the mission as it experiences changes in the operational context and needs during the lifetime of the spacecraft. The time unit of analysis is known as an *Epoch*, with fixed context during operation while uncertain factors that might change across contexts are parameterized using epoch variables. A time-ordered sequences of epochs is called as *Era*. For era analysis, each epoch is assigned a duration and across the sequence of epochs one can consider the impact of path-dependent unfolding of uncertainty.

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