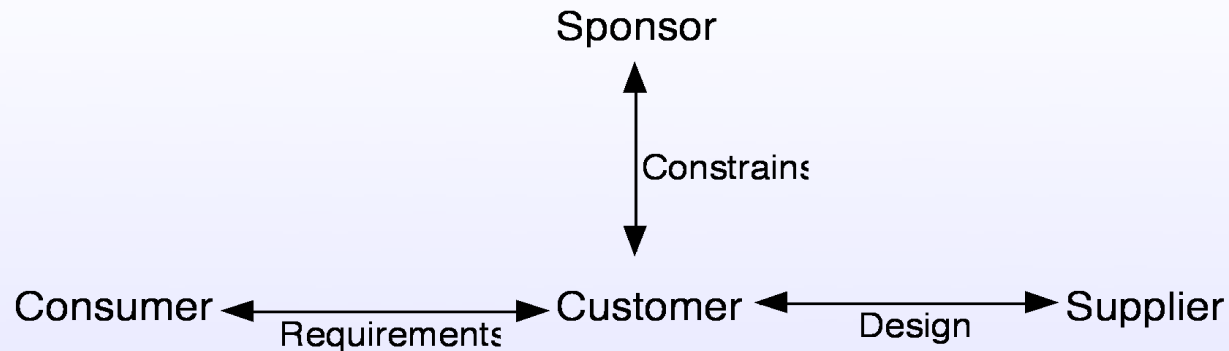


VALUE FOR MONEY IN SPACE MISSION DESIGN

AIM OF THIS PRESENTATION

- The aim of this presentation is to provide an overview of the interaction between
 - It provides a panorama of the space mission including its programmatic environment and the actors involved in the space missions
 - It introduces the relationships between mission specification and mission design
 - It also provides an overview of the relations between science, engineering cost, schedule and risk
- That means this presentation provides an overview of the space mission design process in the context of the needs it fulfils and of the constraints (cost, risk, schedule) it has to respect

ROLES IN SPACE MISSIONS



- The Sponsor, the entity that pays for the system and establishes the constraints, cost, schedule and guidelines, to be applied to the implementation of the space system
- The Consumer, the community who uses the output of the system and who establishes requirements on the quantity, quality and mode of delivery of the data to be produced by the space system
- The Customer, the entity who represents the interest of the Consumer with respect to the Supplier, who specifies the system, oversees its implementation, accepts and certifies it and delivers the system to the Consumer
- The Supplier, the entity who interacts with the Customer, contributes to the preliminary definition and performs subsequent detailed definition, builds the system, tests it and delivers it to the Customer

RELATION BETWEEN REQUIREMENTS AND DESIGN

- In theory the design should answer the requirements
- In fact, there is interaction between design and requirements. The textbook situation where users generate a clear set of needs that produces a clear specification that generates a design, is exceedingly rare:
 - The Consumer of the data to be provided by the space mission have always a wide, and some times contradictory, set of desires that can be partially or totally fulfilled by different designs answering different sets of final performances
 - These designs will have attached different price, risk and schedule tags and would require different programmatic approaches.
 - Furthermore, the scientist (Consumer), who use, and the Sponsor, who pays, will be different entities. The sponsor could have explicit or implicit objectives that, being him the source of the funds, will become fundamental to meet
- This will force a mutual interaction and accommodation between requirements and design. Requirements and design will develop simultaneously not sequentially

SCIENCE AND OBSERVABLE

- The correct definition of a space mission requires the correct understanding of its use and of the 'science' behind its use. This understanding is specially important before project approval while the final requirements are not yet frozen
- It is necessary to understand the algorithms relating the derivation of information about the observable with the quality and nature of the observing instruments
- All proper system design requires the existence of end to end mission performances simulation models. These models shall provide the performances in terms of Consumer final 'science' units and not in terms of space 'engineering' units
- Flexible end to end mission effectiveness models allow to evaluate the final performance of alternative mission implementations. This provides optimal missions in terms of performance divided by cost
- Mission effectiveness figures will also allow the identification of risk and cost discontinuities where a small increase in performance is associated with a large increase in design complication, cost or risk

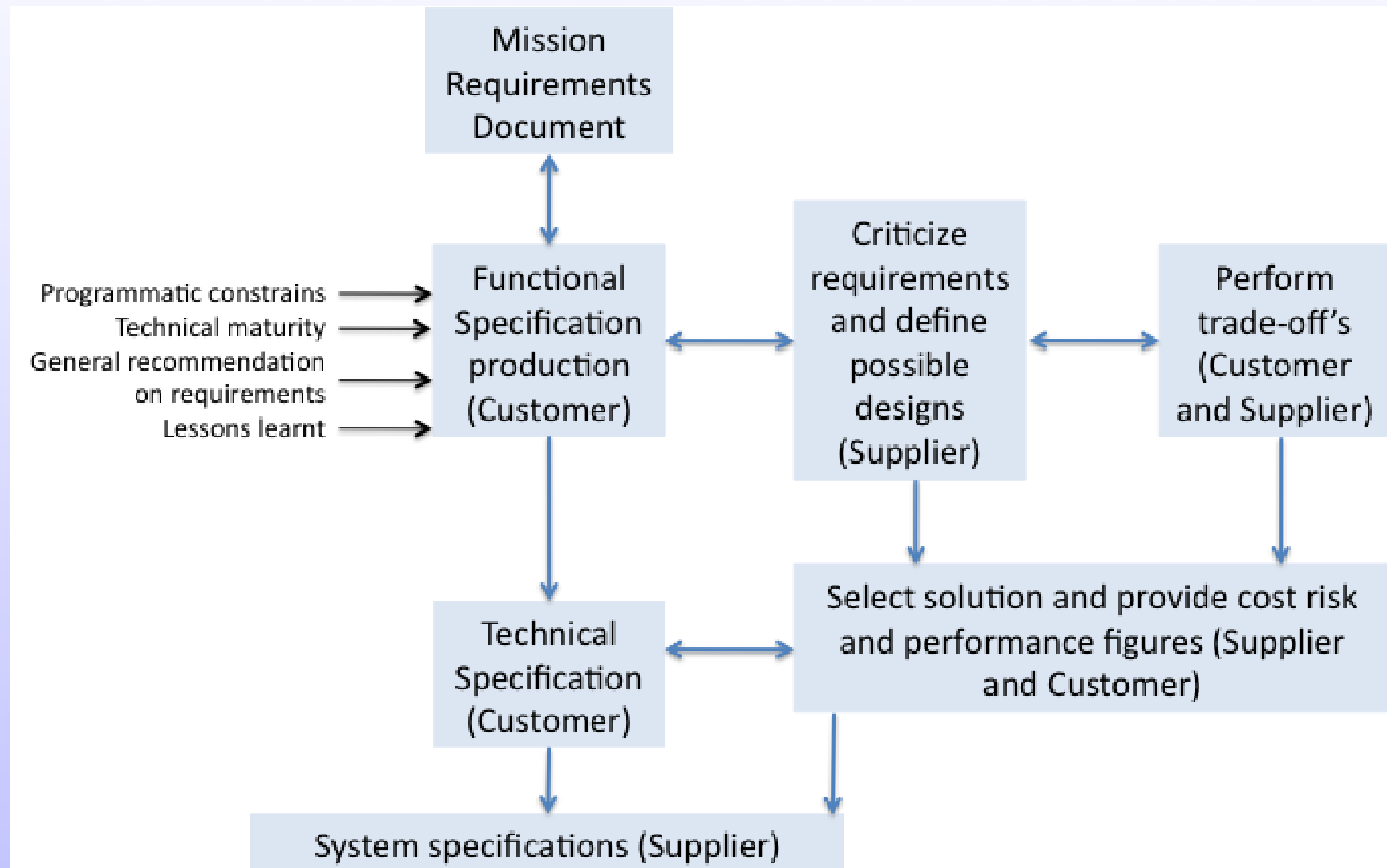
CONSUMER MISSION REQUIREMENTS DOCUMENT

- A system's 'mission' is the specific task, duty or function it is designed to accomplish. In order to begin the process of definition, therefore, the system's mission must be explained. The document fulfilling this task is often called the 'Mission Statement'
- As the process of definition advances, the Mission Statement will generate a 'Mission Requirements Document' where the initial vague needs become progressively more concrete—and often numeric—requirements. This document will list the end-to-end requirements necessary for implementing the system. The Mission Requirements Document formalizes and concretizes the commitments obtained from the Customer by the Consumer
- On the other hand the Consumer does not normally pay for the system and it is the Sponsor's role to provide the funds directly to the space agency, that is, to the Customer. Therefore, independently of how precise the Mission Requirement Document is, it is not legally binding
- The Customer's role as an intermediary between the Consumer and the Sponsor, also explains why the Customer, and not the Consumer usually writes the Mission Requirements Document, which, however must be written from the Consumer's perspective. If the Consumer is a collective of scientists, the document shall be written from the perspective of the science to be produced
- Operational missions—such as operational meteorology—are promoted and financed by a single entity acting as both Consumer and Sponsor. This Sponsor/Consumer would still depend on a Customer (a space agency) for the development and implementation of the system, but the Consumer/Sponsor would control the funds and system needs, would write its own Mission Requirements Document and would establish his own priorities
- These documents shall not imply a design but often imply an observational technique and instrument concept

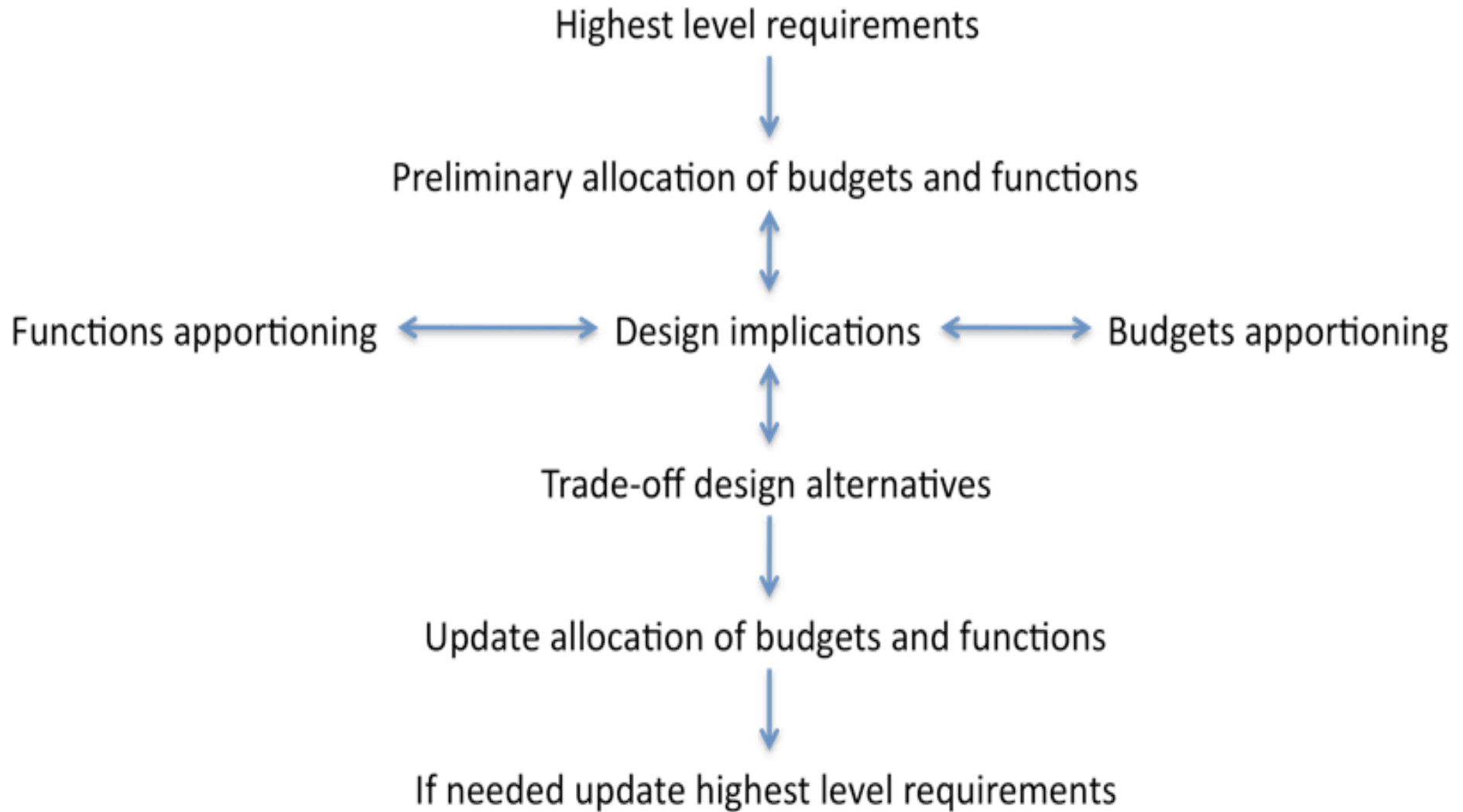
THE CUSTOMER SYSTEM REQUIREMENTS DOCUMENT

- A Technical Specification is a document expressing Requirements for designing, developing and eventually validating and accepting the system being implemented.
- The Technical Specification evolves directly from the Functional Specification and must be free of all ambiguities. The evolution from Functional to Technical Specification is based on the Supplier's analysis of preliminary needs, including suggested possible alternative design concepts, and by the Customer's continued refinement of the original concept, balancing the Customer's requirements, the Sponsor's constraints and the design concepts and difficulties of the Supplier.
- This progressive process of accommodation between ends and means produces the eventual elimination of all ambiguities
- The Technical Specification defines the requirements for the selected solution, and is a legally binding document that will form part of the final contract for the system's implementation. The Technical Specification is the firm base providing credibility to the performance, risk and cost estimations needed for a well-informed decision on whether or not to approve a fully funded project

FROM FUNCTIONAL TO TECHNICAL SPECIFICATION



FROM REQUIREMENTS TO DESIGN AND BACK



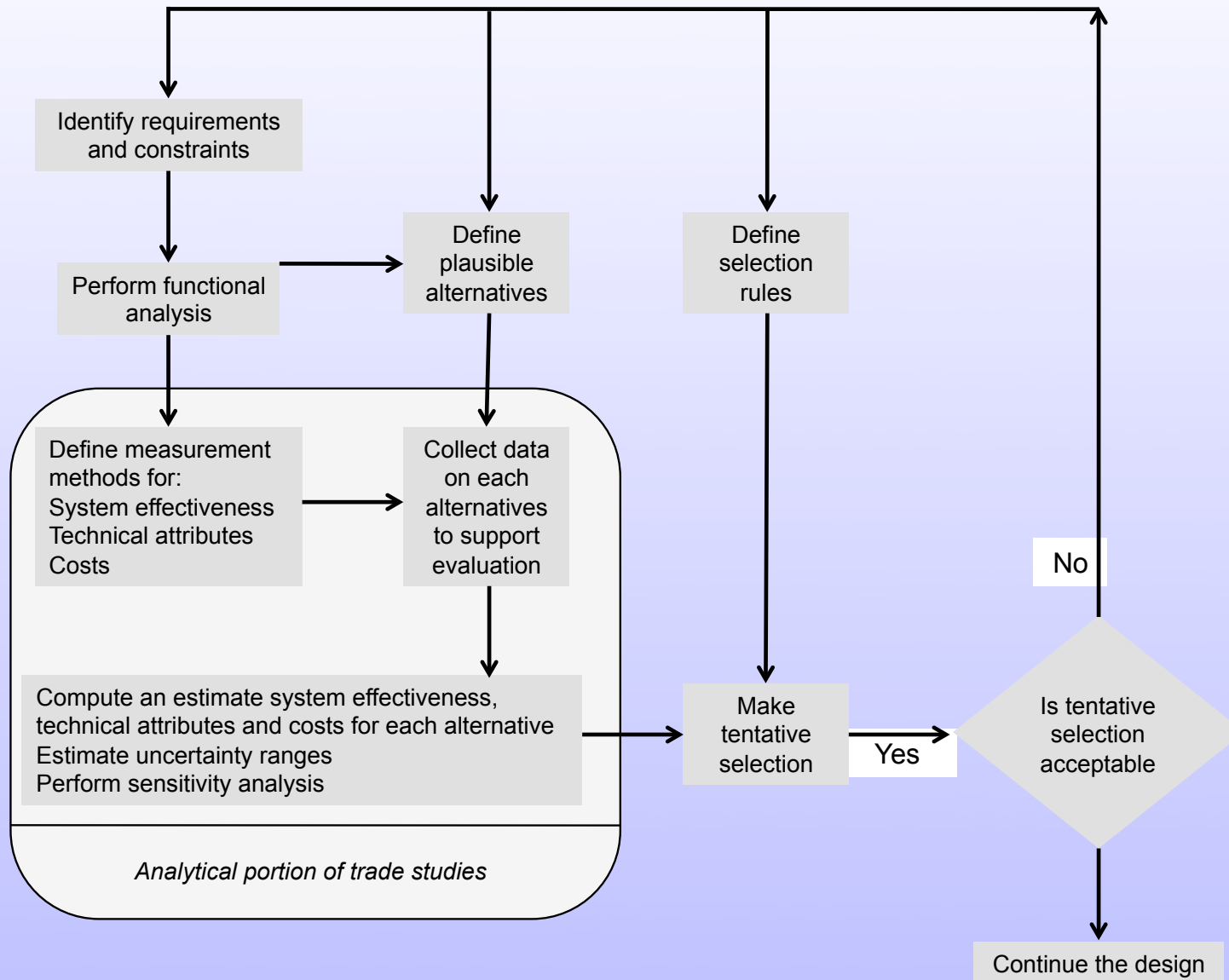
RANKING OF REQUIREMENTS

- To fulfill his contractual duties the Supplier must demonstrate compliance with all requirements; from this viewpoint all requirements are equal. Nevertheless, some requirements are clearly more important than others:
 - Some requirements are absolutely fundamental for the mission to be of any value to the Consumer; for example, missions to study weak astronomical events located far away in the deep space has to be sensitive enough to detect them and accurate enough to characterize them properly. Clearly the requirements related to accuracy and sensitivity would be fundamental for this missions.
 - Some requirements have major impacts in many aspects of the design; the need to flight a satellite at low altitude over the Earth surface, will impact not only almost every subsystem of the satellite, but also the overall data flow and the operations approach.
 - Some requirements are both things at the same time: fundamental for the Consumer and impacting many aspects of the design.
- Identifying the most important requirements is not difficult, since they derive directly from fundamental Consumer needs and because they become the main and most difficult to fulfill from the earliest stages of mission's definition. You do not need to find them, they will find you

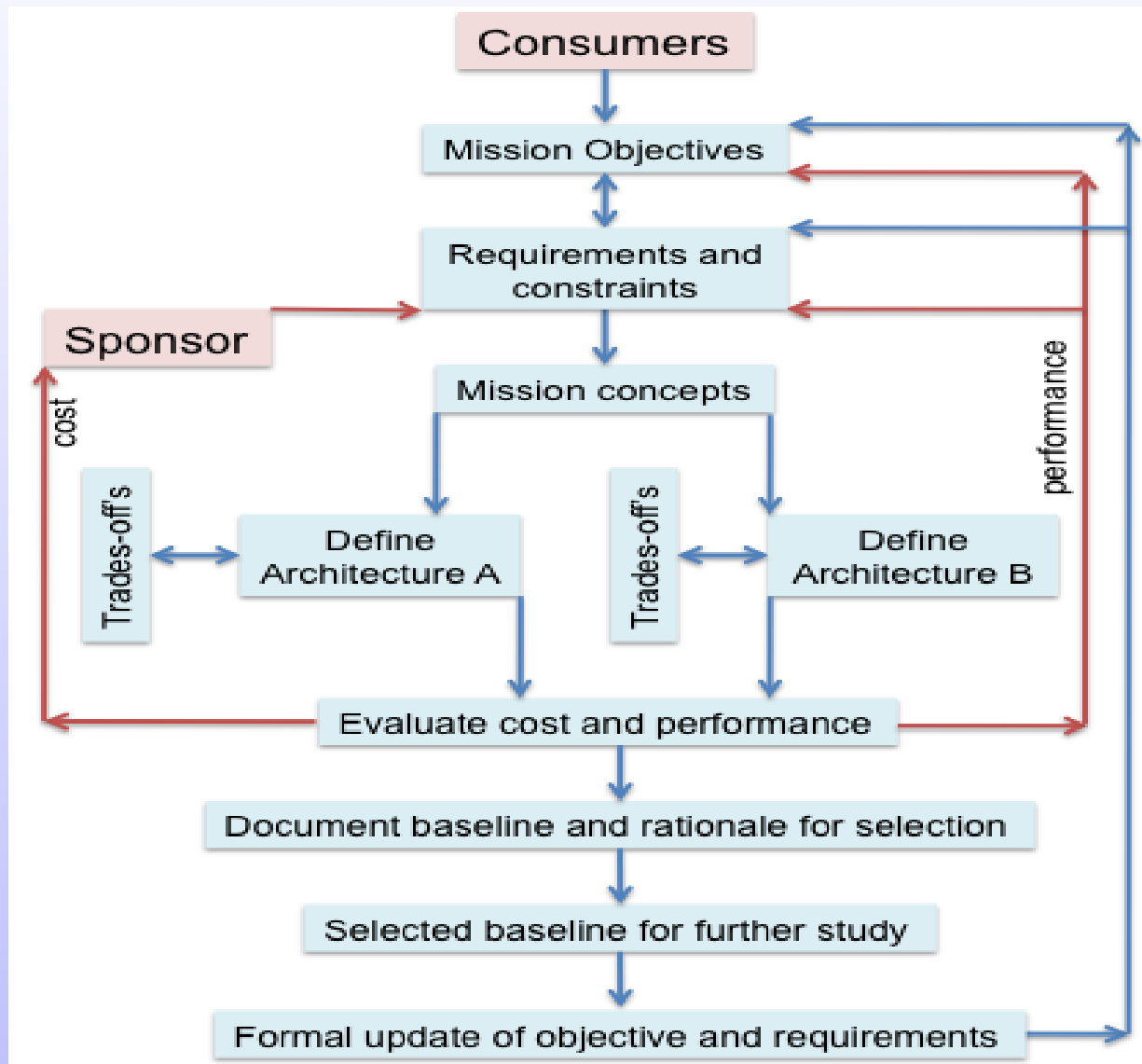
DESIGNING AGAINST REQUIREMENTS

- Design is fundamentally design against requirements. All the presentations on design interactions are on design against requirements
- Nevertheless, Consumer desires can never be transformed in firm and fixed requirements until the Consumer and Sponsor understand the risk and cost involved in its fulfilment
- It is obvious that to reduce performance, that means to relax requirements reduce cost and risk. The mission architecting team will —actually shall— identify what requirements can be relaxed reducing significantly cost and risk while still keeping the Consumer fundamentally satisfied, One clear path for design and requirements accommodation is when requirements are expressed not as a single value but as range of possible performances: threshold, breakthrough and goal
- N. Augustine said that “the last 10% of the performance sought generates 1/3 of the cost and 2/3 of the problems”
- The final value of the mission is the value for its Consumer and the last decision on requirements relaxation shall be in their hands
- At the end of the definition and to provide price and performance credibility all the requirements shall be frozen

TRADE-OFF METHODS

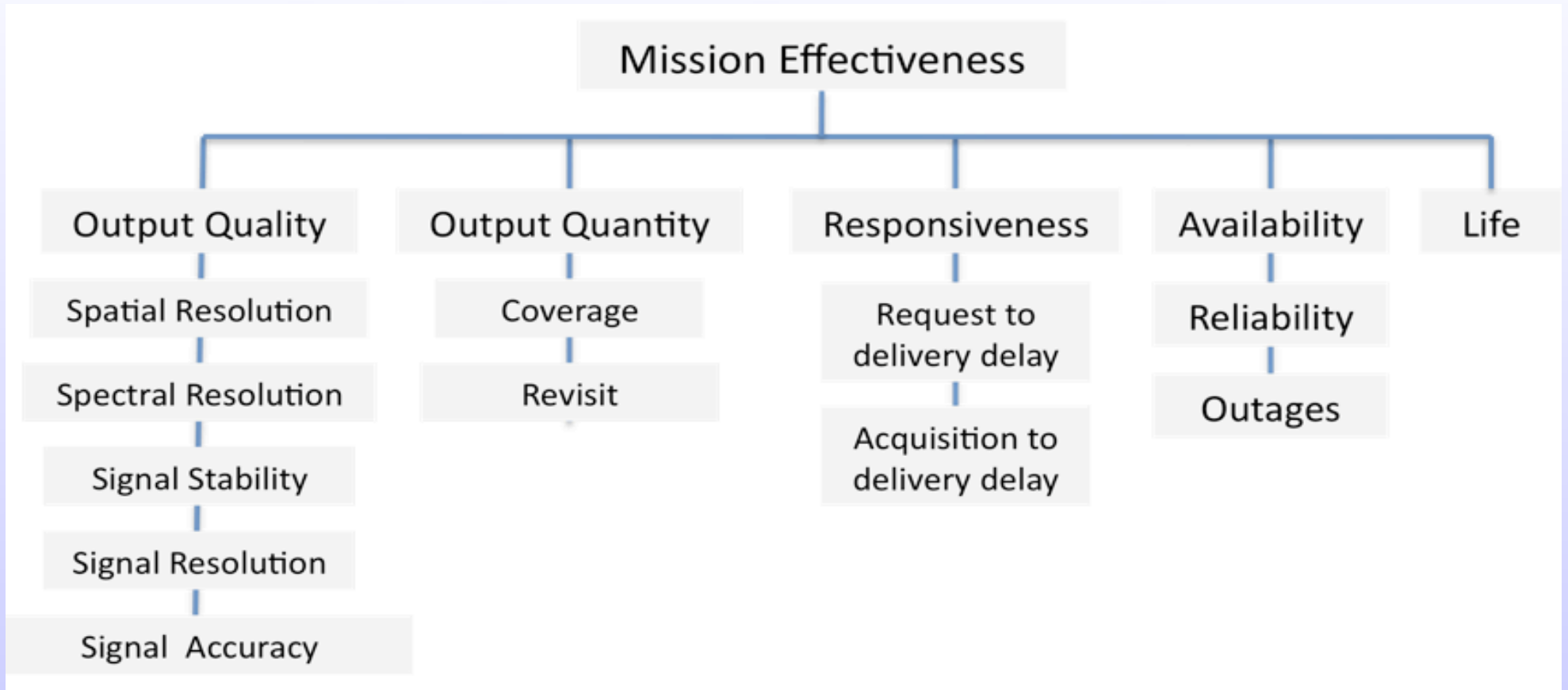


TRADE-OFF'S AND RECURSIVE LOGIC OF DESIGN



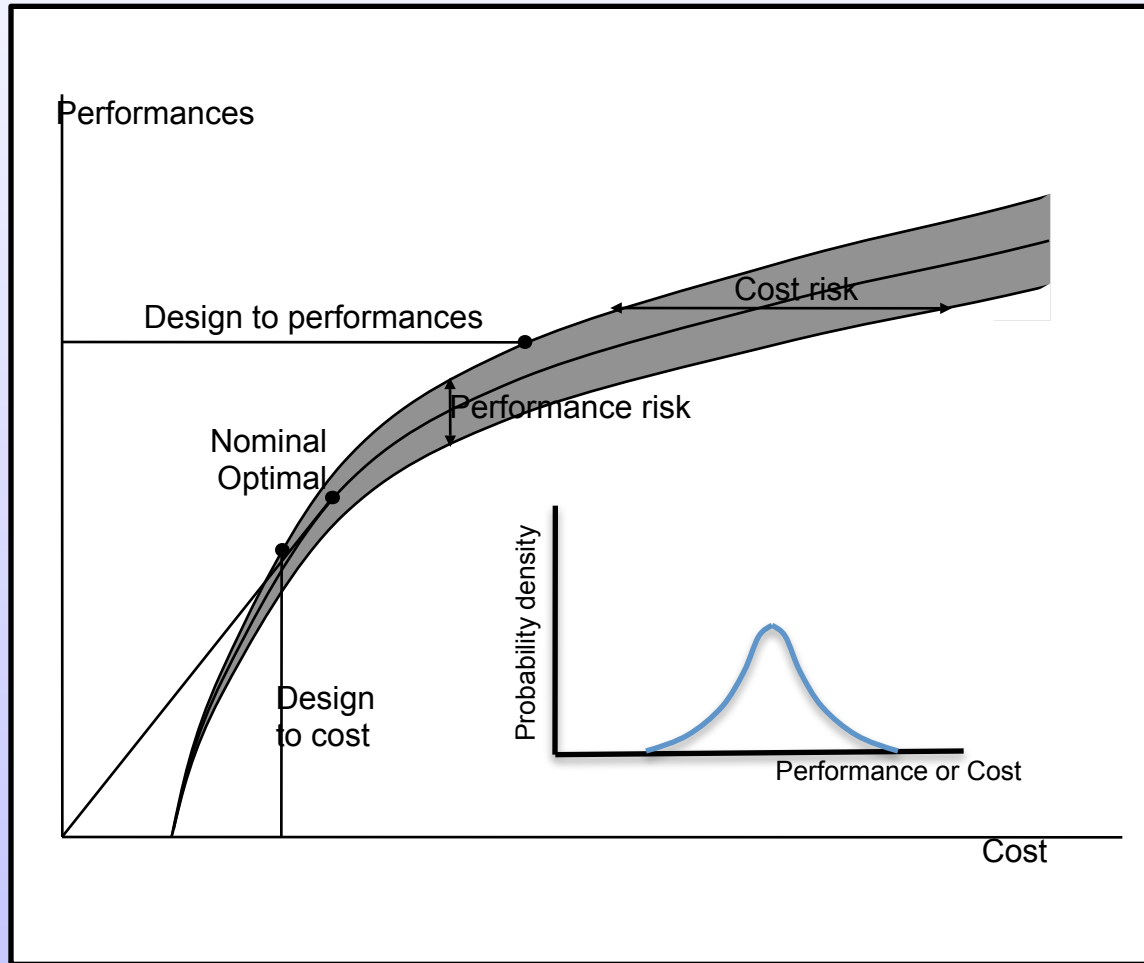
SYSTEM EFFECTIVENESS CLASSES

- We could consider three types of system effectiveness figures
 - Output quality figures, which determine to what extent the mission products are able to provide high accuracy information. True end-to-end quality figures are expressed in the relevant observational units, thus, ocean currents recovery accuracy would be expressed in m/s. Instrument requirements, however, are expressed in instrument units: swath, bands, noise to signal ratio... etc. Output quality figures needs the involvement not only of space engineers but also of the Consumer
 - Output quantity figures, output quantity figures are simple to produce and understand and can be generated with the sole aid of space engineers. Satellite life and instrument swath are parameters of this kind
 - Responsiveness figures. Some of them, such as data delivery delays, are straightforward numerical values. Other measures of responsiveness, for example the possibility Consumers to modify their observational needs at will, are not directly numeric and require interaction between Consumer and Customer to reach a clear understanding of what the real needs are
- These three classes of system effectiveness could be integrated into an single value mission performance, which permits the definition of optimal design points; nevertheless, actually obtaining a trustworthy single value for system effectiveness is often not a realistic goal because quality, quantity and responsiveness figures are not easily commensurate



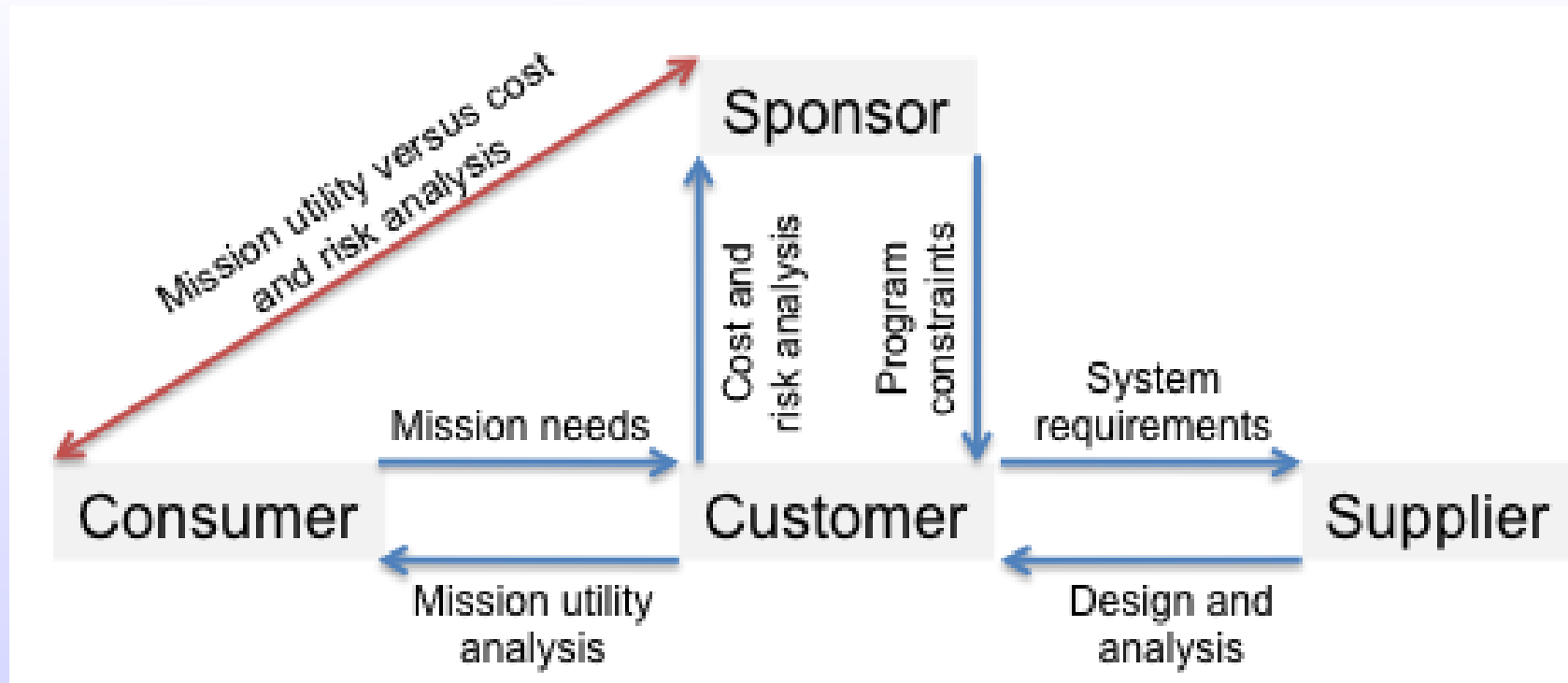
- There are multiple important and meaningful numerical mission effectiveness value
- It would be 'in principle' possible to allocate weighting factors and to provide a single integrated numerical mission effectiveness or mission performance value

DESIGN SPACE AND OPTIMAL DESIGNS



- It is possible to provide a performance as a function of cost. This will define a design space
- Actually performances and cost will not be fixed values but probabilistic distributions. In this view, three situations are possible:
 - To design to Consumer requested performance requirements. This will generate a larger cost risk
 - To design to Sponsor specified costs. This will introduce a smaller performance risk
 - To try to identify an elusive optimal design that maximises the return performance/cost

MISSION EFFECTIVENESS

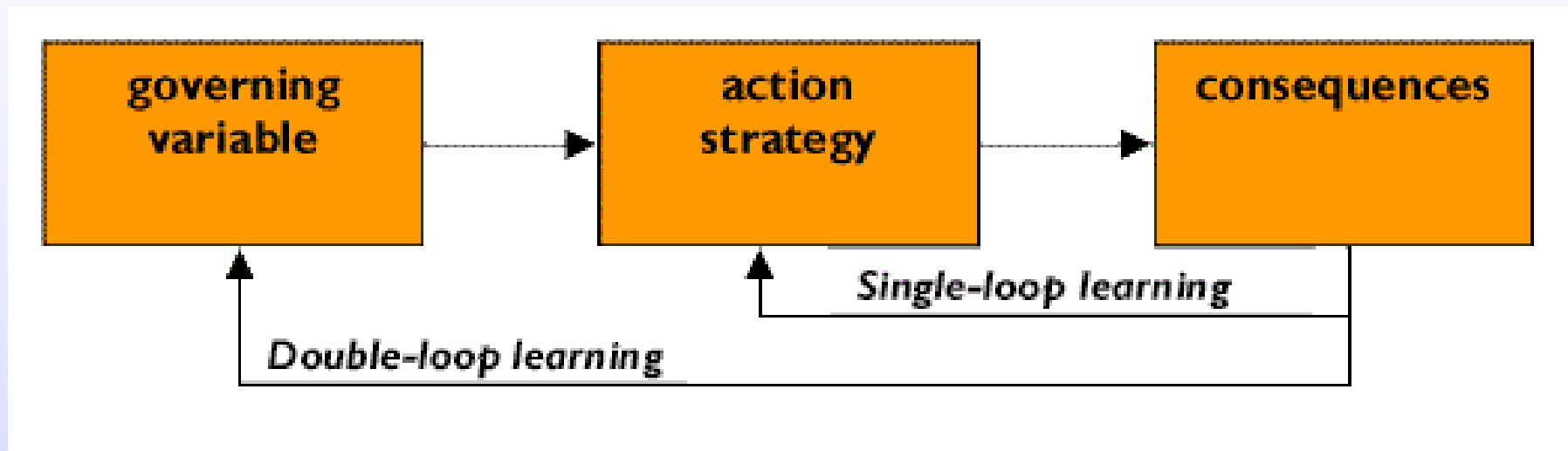


- Mission effectiveness parameters will provide an integrated measurement of the value of the mission.
- The availability of system effectiveness figure allows to compare concepts and rank them in terms of satisfaction of Consumer needs. This will also allow the determination of performance/cost optimal

EFFECTIVENESS METRICS LIMITATIONS

- Practical effectiveness models only include one or a few of the many possible key requirements of special importance for the Consumer.
- The models supporting the different steps necessary to provide a true system level effectiveness figure may not have been properly integrated.
- Furthermore, performance scale is not linear. There could be: small improvements of dramatic importance. A system whose aim is to survey the whole Earth will not produce 90% of satisfaction if it only surveys 90% of it
- Models always include assumptions about the real world and they always leave something out. They are only able to produce accurate results when addressing quantifiable parameters in which the physics of the derivation of the figures is well understood and **dealing with highest-level system definition issues this is not normally the case**
- The model will produce insights but it cannot provide definitive answers to the substantive questions on its own. In the other hand, the resulting insights are fundamental tools for system definition but the designers shall

THE EXTERNAL ENVIRONMENT



- Any space Project sits inside a larger environment. From a thermodynamic point of view, space design is an open process that interacts with its social, political technical and economic environment and that can adjust its behaviour and goals as an answer to these external influences. The result is a servosystem with external loop and an internal loop
- The reaction of the external environment could force the designer to change the objectives set by the mission requirements. This double loop image is in line with the approach of these presentations, which considers the space architecting process as interactive between Consumers, Sponsor, Customer and Supplier

EXTERNAL ENVIRONMENT

- Social. The changing social perception of space itself will influence what space system could or could not become a reality. This social perception can change in different directions for the different fields of space research: it could improve or degrade for Earth Observation with respect to Astronomy or Crewed versus Robotic research
- Technical. Space design is fundamentally a technical activity and the technical environment cannot be considered 'external'. During the design phases, technology readiness analysis will characterize the problem and risk retirement approaches, and specific technical developments will be recommended to reduce the technical risk
- Economic. Public or private, the feasibility and optimal design for a space system will depend on the economic environment. Most space endeavor is government funded; the status of public finances, which depends of the economic environment, will discourage or encourage the implementation of more or less ambitious space projects
- Political. The overwhelming majority of space projects are done with government money. It's a legitimate concern for political representatives to care about the use of public funds. This makes the approval and implementation of any space project a political process

REQUIREMENTS VERSUS CONSTRAINTS

- These presentations divide the factors influencing the material and programmatic design of a space system into two types: Requirements and Constraints.
- Requirement: anything that is included in a formal specification and that will be verified during the implementation process. It is internal to the project, explicit and, during the architectural design phases of a project, can be negotiated and perhaps modified. The Consumer is normally the source of Requirements
- Constraint: anything that limits or affects the system design or implementation. It can be implicit or explicit and can be external to the project. Frequently cannot be modified or negotiated. The Sponsor is normally the source of Constraints
- Constraints could include such things as the need for the project to be dedicated to a specific purpose, being below a given cost, completed within a given time length or being launched using a specific launcher. Political, 'hidden' constraints can also strongly drive the design, e.g. the Apollo program real requirement was to demonstrate the superiority of Capitalism over Communism

TYPES OF PROJECTS BY AIMS

- Capabilities demonstration are mission that need to demonstrate that the organisation leading the mission has the capability to implement it successfully. The drive is fundamentally a political drive by the Sponsor. these missions shall be designed so that risk of failure is minimised, while cost is kept within bounds and that high quality scientific output or a long mission life are welcomed but not compulsory
- Technology demonstration missions want to verify in-orbit a technical development related either to a specific observing technique or to satellite platform technology. These missions are risk tolerant, cost limited, and can have a short life. They are driven by the needs of the Customer or Supplier
- Advancement of sciences. The aim of an advancement of science mission is to solve a well-defined scientific problem. It has to produce data of a specified quantity and quality. It is driven by the scientific Consumer. These missions must be designed to be successful and use advance technology, but they are cost limited. They need to provide the specified data quality and life
- Operational missions answer specific 'permanent' societal needs. The fundamental driver for these missions is the long term and reliable provision of data of consistent and acceptable quality. It is driven by the operational Consumer. These missions don't require normally pushing the state of the art. Long life is strongly desired

SATELLITE COSTS

- The first thing to be said is that the obligation to 'design to cost' applies to all projects, not just those projects that have a 'design to cost' label. Minimum cost design is not a special way of doing engineering is just engineering
- The cost of the implementation of a mission is not only the cost of the satellite; a proper estimation of the cost of new space systems shall be end-to-end and include all the non satellite acquisition costs:
 - Customer internal costs
 - Launcher
 - Satellite operations
 - Data Utilization
- The most important element for taking into account non-satellite costs is transparency. It must be very clear what is included and what is not included, and why. Some programs could put off-budget such elements as the launchers, data utilization, the instruments or the platform. If these are the rules of the program, the designer must follow them. Nevertheless, a correct design shall take into account the overall cost to the taxpayer. The existence of these off-budget cost can produce unbalanced designs; for example a sophisticated instrument flying in a not adequate standard platform and using a unnecessarily large launcher. Check TOMS Earth Probe large platform for a very small payload (in white).

BOTTOM UP COST ESTIMATIONS

- Bottom-up cost estimation proceeds by dividing all the work to be done in packages and by estimating the price of each one of them. The finer the division of the work, the larger the number of work packages and the more comprehensive the final cost estimation.
- The estimation of each one of the packages is done by consultation with experts with experience in the cost of similar packages done in the past. The final cost is the addition of all the individual costs.
- To create a detailed bottom-up cost estimation requires a large amount of effort and it cannot be repeated many times during the process of definition of a space mission. It is also evident that to be able to provide a high quality prediction of the cost of the mission is necessary to have a fairly detail level of design including a rather detailed approach to the development and to the test philosophy; test is one of the main cost drivers.
- Detailed bottom-up cost estimations are normally produced by the Supplier and delivered to the Customer when the definition phases of the possible new mission are finished. The bottom-up cost estimation will be discussed between the Supplier and the Customer and will be finally provided to the Sponsor to provide credibility to the cost estimations.
- Bottom-up cost estimations are management documents and used mainly for management purposes. When the Supplier provides it, he commits himself not only for an overall cost but also for a detailed decomposition. For this reason, the Supplier will deliver the cost estimation only when reasonably sure of the credibility of the estimation

TOP DOWN COST ESTIMATION

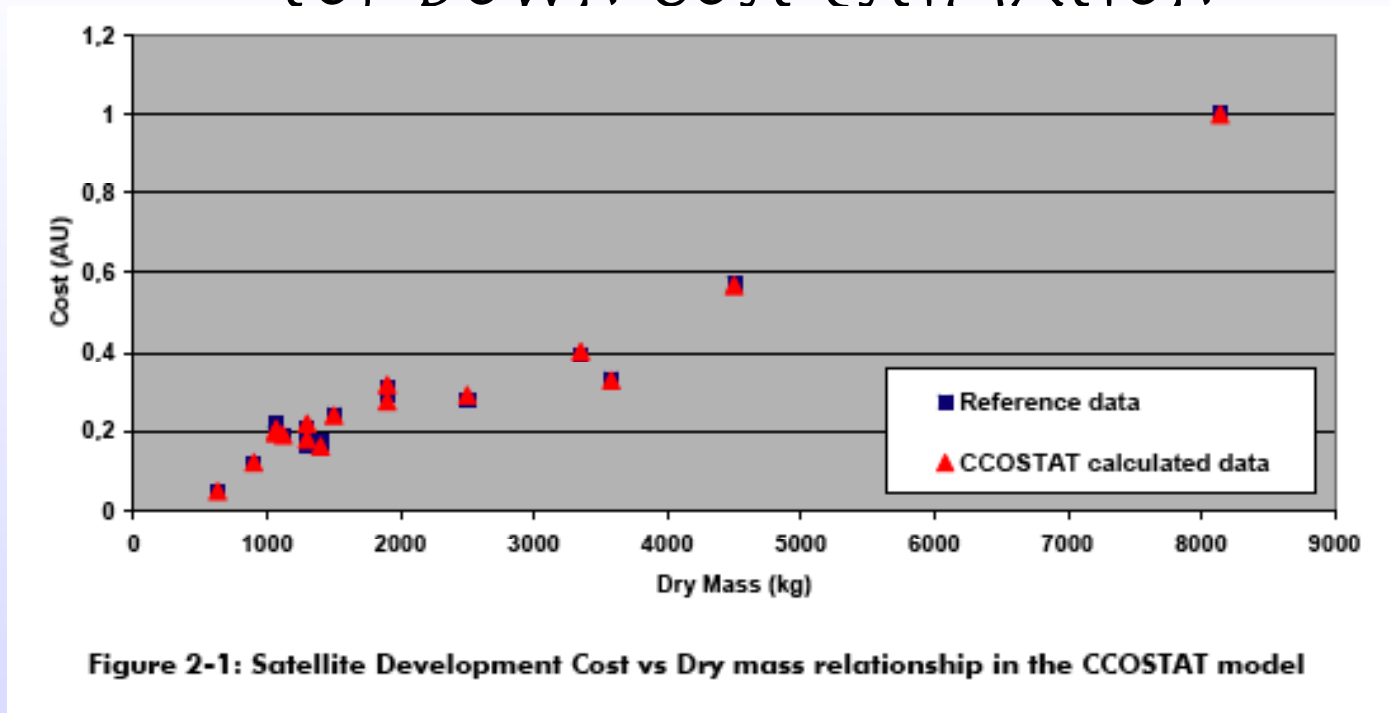


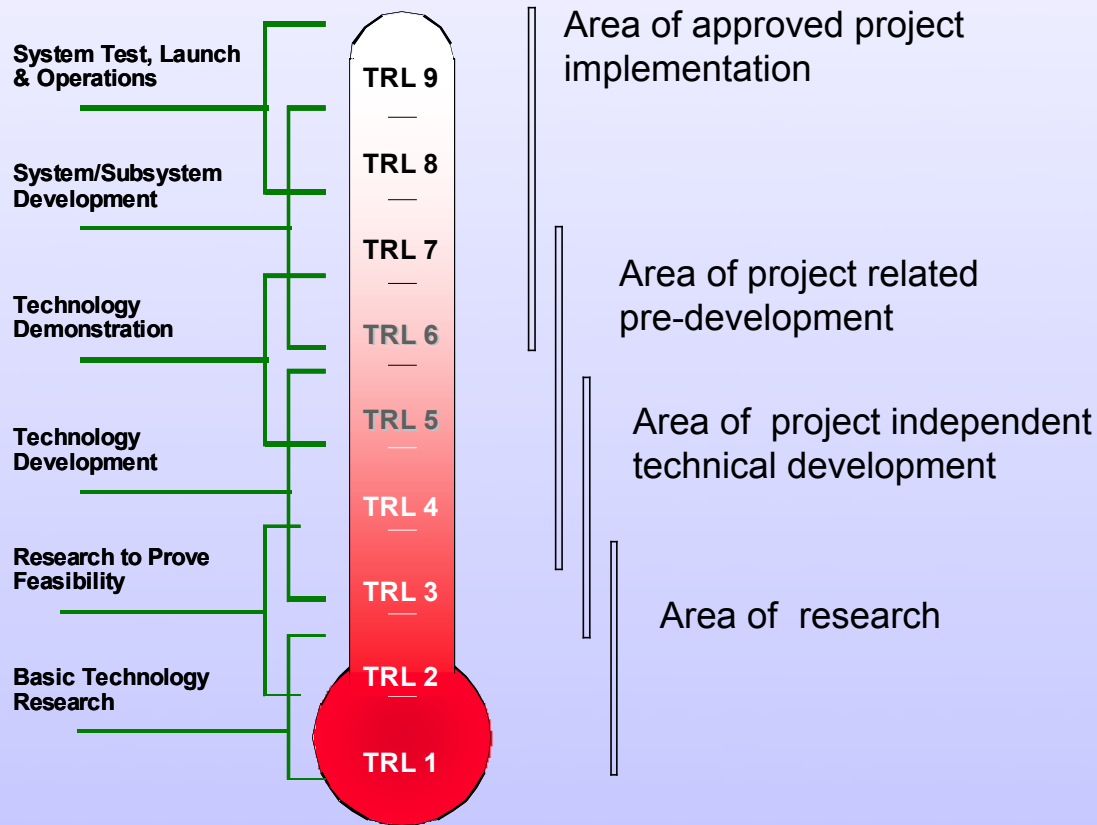
Figure 2-1: Satellite Development Cost vs Dry mass relationship in the CCOSTAT model

- Top down cost estimations provide estimations of the cost of a satellite, which is normally the most important cost of the overall space system, as a function of the satellite dry mass and of the satellite innovation level.
- Top down cost models are obtained by creating databases of cost of past similar satellites and deriving correlations between cost, mass and innovation level
- The figure above provides an example of application of the method. The model is fed with data from a number of projects. The mass and the cost are numerical know data. Innovation is finally reduced also to a numerical parameter function of the inheritance, or novelty, of the satellite with respect to the previous missions that have been used to create the cost model database
- Once that the model is created it can be used flexibly to estimate the cost of alternative designs. Top down cost estimations are tools adequate to help trade-off's

RISK CONSTRAINTS

- The management of risks includes :
 - The systematic identification, evaluation and classification of all risks causes and consequences
 - The systematic definition, implementation, control and verification of actions appropriate for the elimination of risks or their reduction to an acceptable level.
- The estimation of risk is based on the assessment of all risk from the point of view of: likelihood of an event occurrence and severity of the consequences of the event occurring.
- The severity of consequence is divided in:
 - High, if the event would impede the achievement of the commitments formally made with respect to the Consumer or Sponsor for a programme or project
 - Medium, when the event would affect the achievements of the committed performance or planned schedule or costs, typically taking months to restore the situation or requiring funding beyond plans within the approved margins
 - Low, when the event would, at the most, affect the planned distribution of performance, schedule or cost, typically taking a few weeks to restore the situation and possibly requiring redeployment of project resources
- The likelihood of occurrence is divided in:
 - High, when the event is very likely to occur, and planned or controls are not available or cannot be put in place to prevent the risk or the consequences from materializing.
 - Medium, when the event is likely to occur, or current plans or controls are not expected to prevent the risk or the consequences from materializing, and substantial additional actions would be required
 - Low, when the event could occur, but is not likely, or current plans or controls are expected to be sufficient to prevent this type of event or its consequences from materialising

TECHNOLOGY READINESS LEVELS AND RISKS

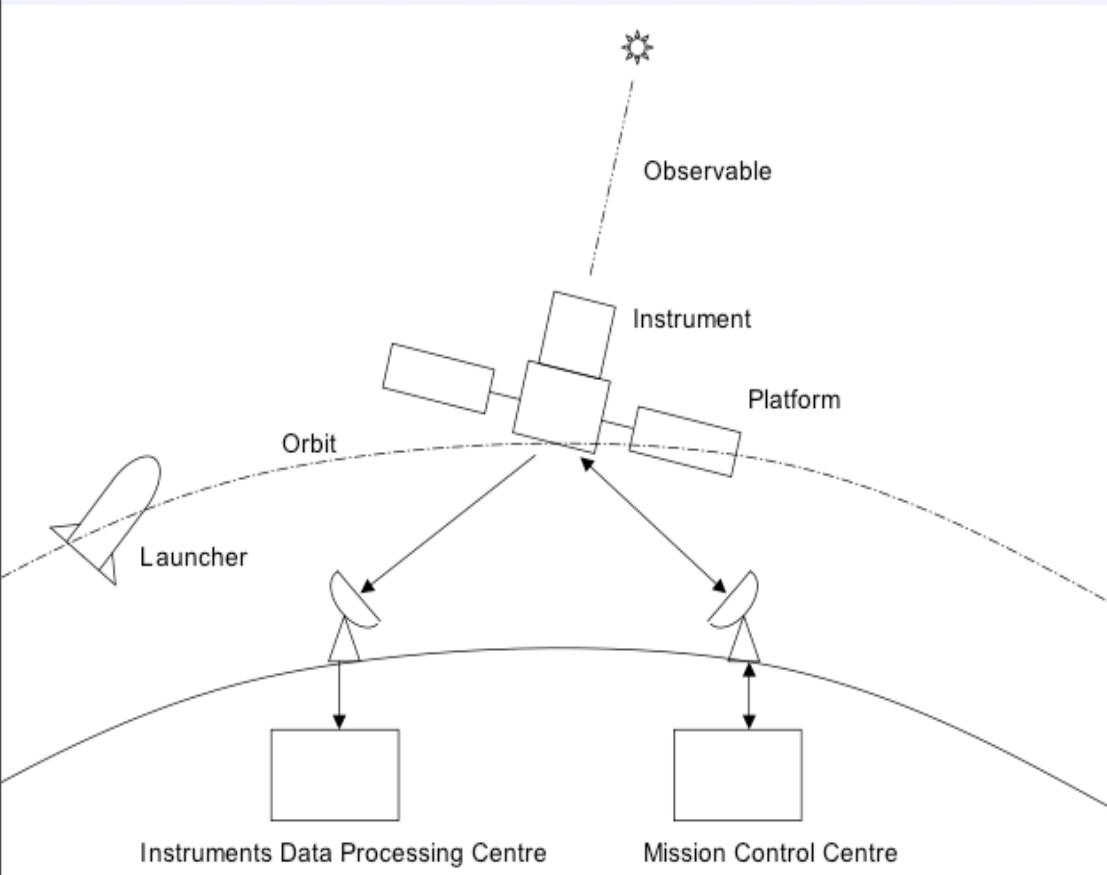


- When a new mission is proposed, it already has a pre-existing body of technical research available that it can identify and use.
- The full fledged implementation of a space project is not advisable before the technology is ready (TRL 5-6)
- During the definition stages of the new mission, the status of the technology will be studied and this will allow identifying areas that are already well developed and areas where there are gaps.
- As the level of technology maturity grows, the risk associated to the space mission decreases
- Low technology readiness at the start of a project is a very important risk driver

SCHEDULE CONSTRAINTS

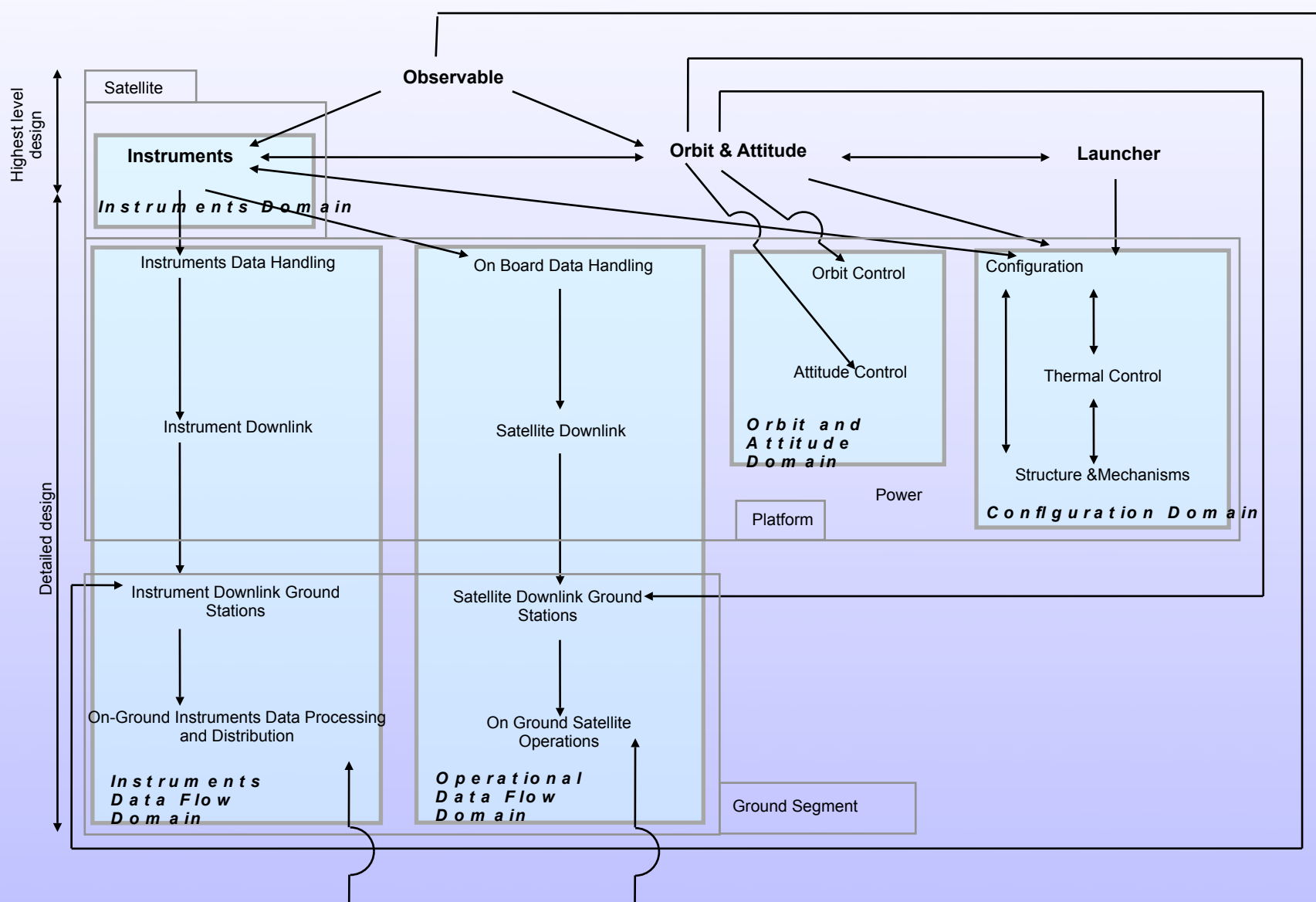
- Any space endeavour is a set of activities that are connected in time, the number and complication of the activities, the need to perform these activities in series or the possibility of doing them in parallel and the level and quality of resources available for the execution of the work will directly derive the schedule of the whole endeavor and of each one of their parts.
- To determine the expected duration of any endeavour it is necessary:
 - To divide the whole endeavour in individual activities with clear beginning and end.
 - To determine by consultation with experts, the necessary duration to each one of the activities. The durations will be function of the level of resources —human and material— available for the execution of each activity.
 - To allocate resources to the different activities
 - To establish logic links of precedence between the beginning and the end of the activities; for example, the manufacturing of an item cannot start before it has been designed.
 - To determine the longest duration 'critical path' sequence of logically linked activities running from the beginning to the end of the endeavour. The addition of these activities will determine the duration.
- That means, the schedule of a project is not an independent parameter. The time needed for project implementation will derive directly from the development approach and model philosophy, which will be a function of the level of novelty of the design proposed and of the failure tolerance of the project

SPACE SYSTEM ELEMENTS



- Observable: the events we want to observe about.
- Orbit: the path of the satellite
- The Launcher: the device that injects the satellite into space
- instruments: the device that obtains the information over the phenomena under study
- Platform: the device that supports the instruments, allows them to fulfil their functions and send to and receive from information from ground.
- Operational Ground Stations and Mission Control Centre.
- Instrument Downlink Ground Stations and Instrument data processing and distribution.

REQUIREMENTS FLOW, DESIGN LOOPS, DESIGN INTERACTIONS AND RESULTING DESIGN DOMAINS



SCIENCE AND OBSERVABLE

- The correct definition of a space mission requires the correct understanding of its use and of the 'science' behind its use. This understanding is specially important before project approval while the final requirements are not yet frozen
- It is necessary to understand the algorithms relating the derivation of information about the observable with the quality and nature of the observing instruments
- All proper system design requires the existence of end to end mission performances simulation models. These models shall provide the performances in terms of Consumer final 'science' units and not in terms of space 'engineering' units
- Flexible end to end mission effectiveness models allow to evaluate the final performance of alternative mission implementations. This provides optimal missions in terms of performance divided by cost
- Mission effectiveness figures will also allow the identification of risk and cost discontinuities where a small increase in performance is associated with a large increase in design complication, cost or risk

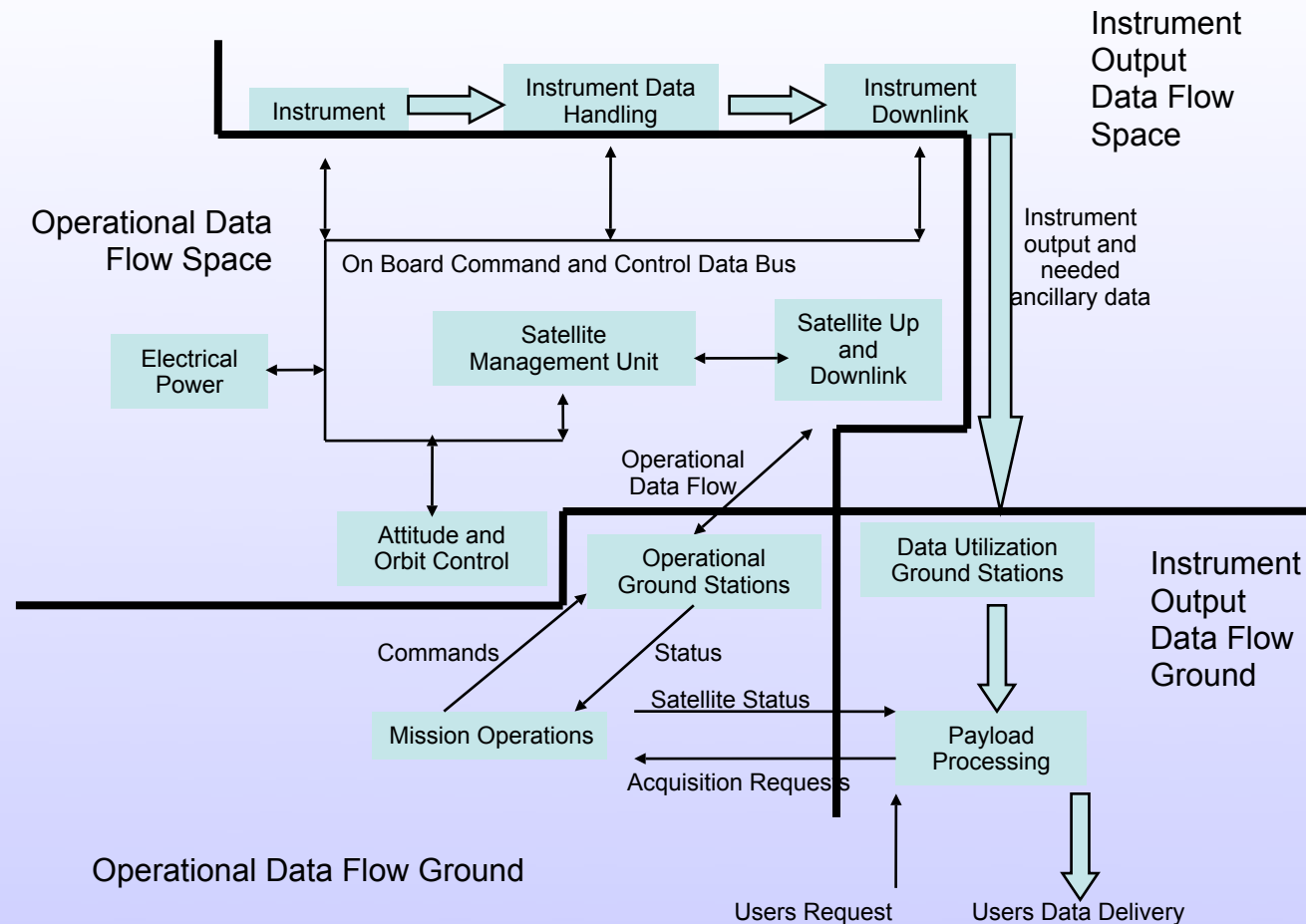
ORBIT AND ATTITUDE

- The orbit and attitude includes the satellite orbit and attitude control functions
- The selection of orbit and attitude is the centre of the highest level design loop.
- There are three possible situations between observable and orbit:
 - The observable is measured 'in-situ'. In this case the orbit shall travel through the observable
 - The observable is on the surface of the body being orbited. In this case the orbit altitude defines the distance to the observable
 - The observable is far away over the heavenly sphere. In this case the distance to the observable is independent of orbit altitude
- There are two possible situations between observable and attitude
 - The instruments do in-situ observations and the attitude is not driven by the observable
 - The instruments do remote sensing and the satellite shall point the instruments in the direction of the observable
- Orbit and attitude are driven by observable and instruments but drive all the other domains: configuration, launcher selection, operational data flow and instruments data flow

THE SATELLITE CONFIGURATION

- The configuration is the shape of the satellite and this domain includes all the satellite mechanical/thermal subsystems plus the solar array as a mechanical subsystem. It is driven by:
 - The need to provide the right observing geometry, for the: instruments, antennae, thermal radiators, solar array
 - The need to provide structural support during assembly and launch
- This drives two configurations: stowed and deployed
 - The satellite is stowed on-ground and during launch. Stowed, the satellite needs to be compatible with the launcher volume. It also needs: strength and stiffness as required by the launcher but also by the on-ground load environment: assembly, test and transportation of the satellite.
 - In-orbit the instruments will require not only an adequate line of sight to the observing target, but also a proper view of cold space for heat dissipation. Electromagnetic emitters and receivers either for satellite communications or detection of observables shall be located to avoid interference. The position and orientation of the solar array must be adequate for acquiring the necessary amount of solar energy. The thermal radiators shall have a clear view of the deep space and shall be protected from the Sun
- When deployed, the configuration is driven by the need for open fields of view and separation. When stowed inside the launcher the satellite configuration is driven by the need for compactness. Mechanisms are used to solve this contradictions

SATELLITE END TO END DATA FLOW



- These presentations divide the overall data flow of the mission in two domains:
 - The operational data flow that deals with the operations of the satellites
 - The instrument output data flow that deals with the utilization of the data produced by the satellite
- The requirements flow and nature, the structure of the interrelation and the necessary skills make this split logic

THE SATELLITE OPERATIONS DATA FLOW DOMAIN

- This domain deals with the functions that the end-to-end space system must perform to operate correctly
- It includes in-orbit and on ground components necessary to operate the satellite:
 - on board data handling and satellite –and instruments– command and control components
 - Bi-directional communications
 - Ground stations and mission control centers
- The operations are drive by how the observable shall be monitored
- The driver of this domain is how to operate the mission and how to obtain the data on the observables. Operations can be:
 - Systematic. Systematic instruments work continuously without requiring frequent ground operations intervention. This allows for a highly autonomous operational data flow with rare human intervention
 - Interactive –observatory like– instruments requires the handling of user requests to observe specific targets. The resulting observing schedules can change frequently and even suddenly. This requires intense interaction between space and ground observatory-like

THE INSTRUMENT OUTPUT DATA FLOW

- This domain deals with the function that the end-to-end system must perform in order to process the acquired data and deliver them to the Consumers
- The domain is driven by how much data shall be produced and how fast it shall be delivered
- It includes:
 - The data processing of the instrument output and its in-orbit processing and storage
 - The modulation and downlink of the on board produced data
 - The ground stations and the ground data processing to generate the mission products
 - The interfaces with the users to receive requests and deliver mission products
- The design drivers are:
 - Data volume
 - Data latency requirements