Science operations of Space missions

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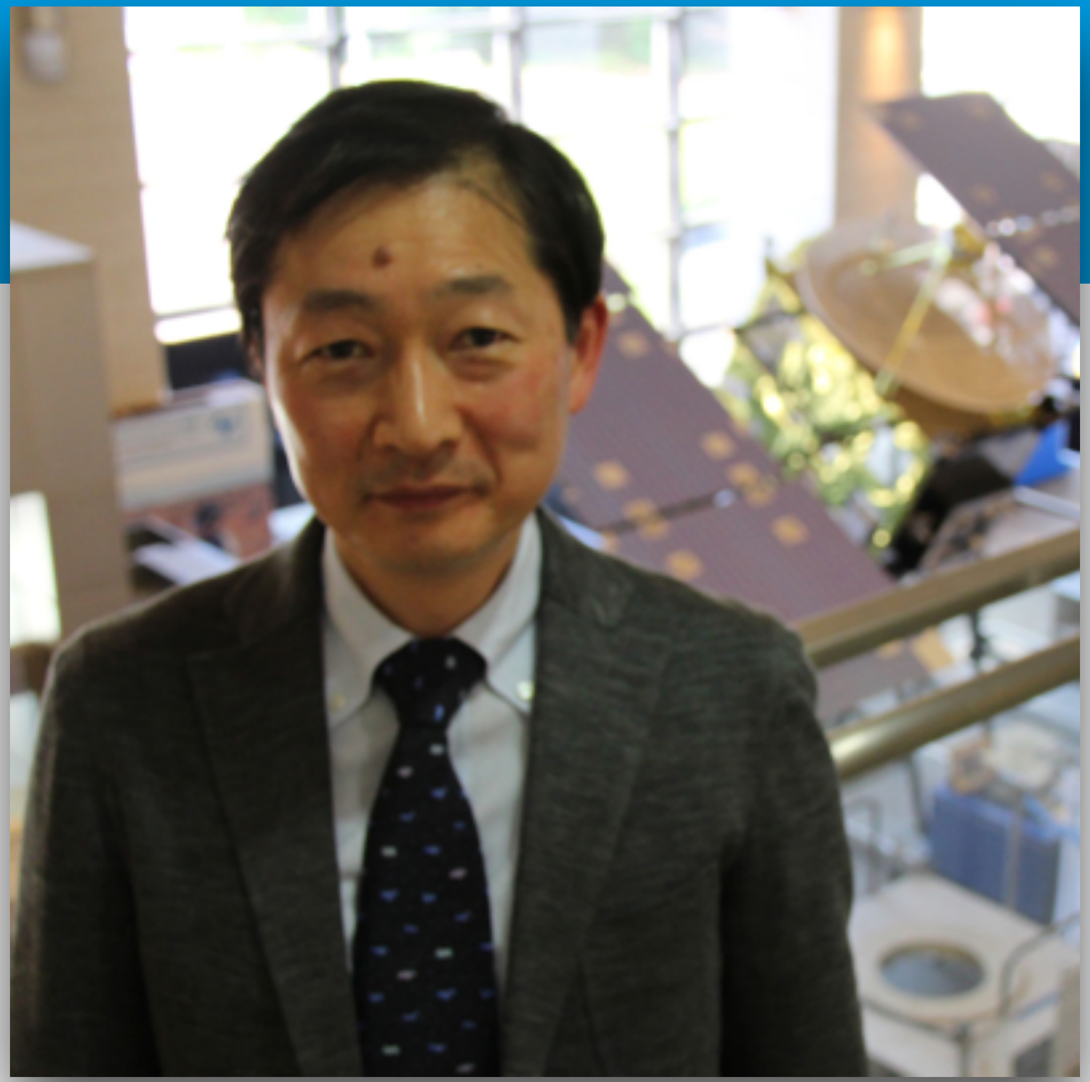
Self introduction



Research Director and Engineering Manager,
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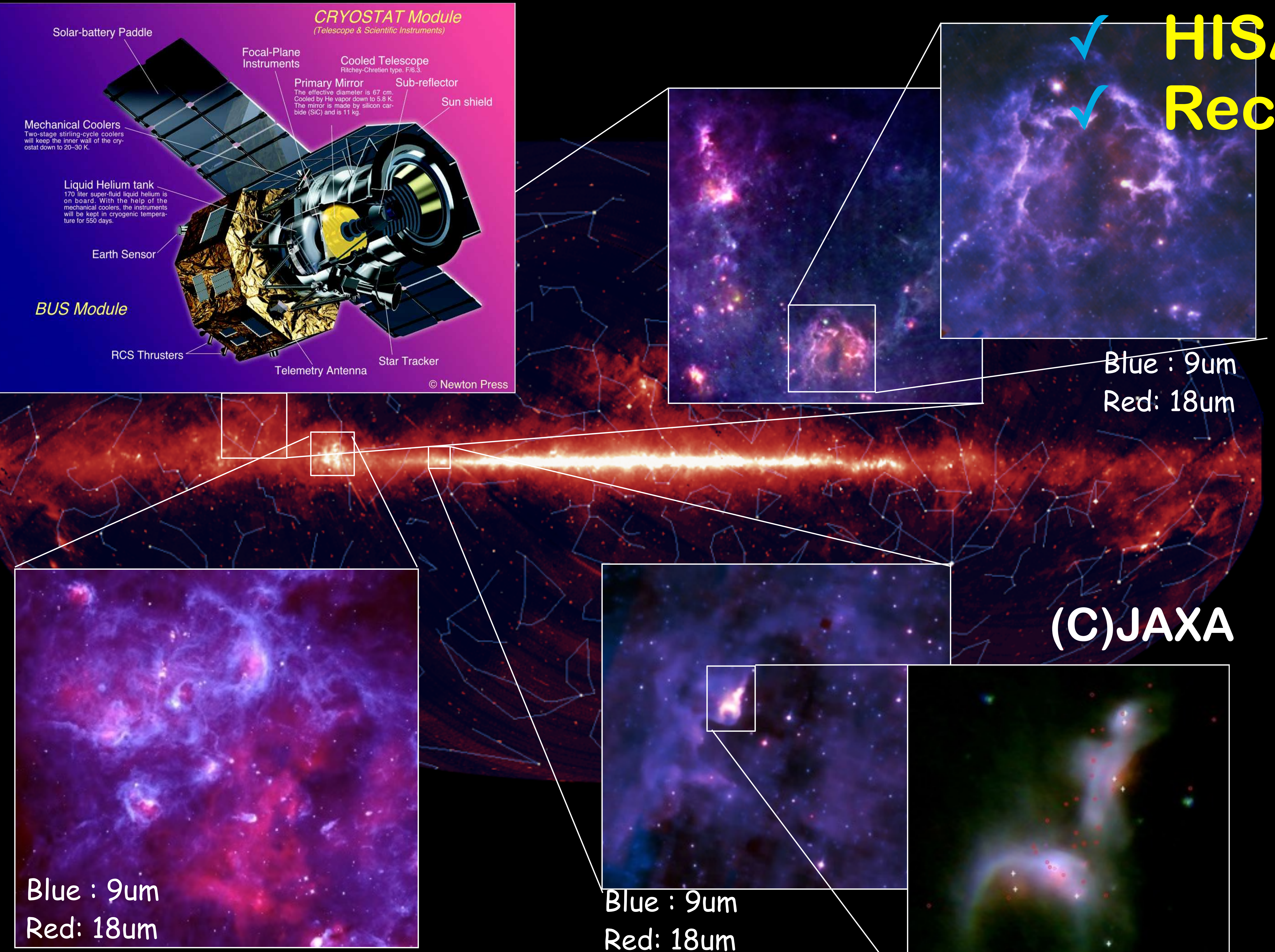
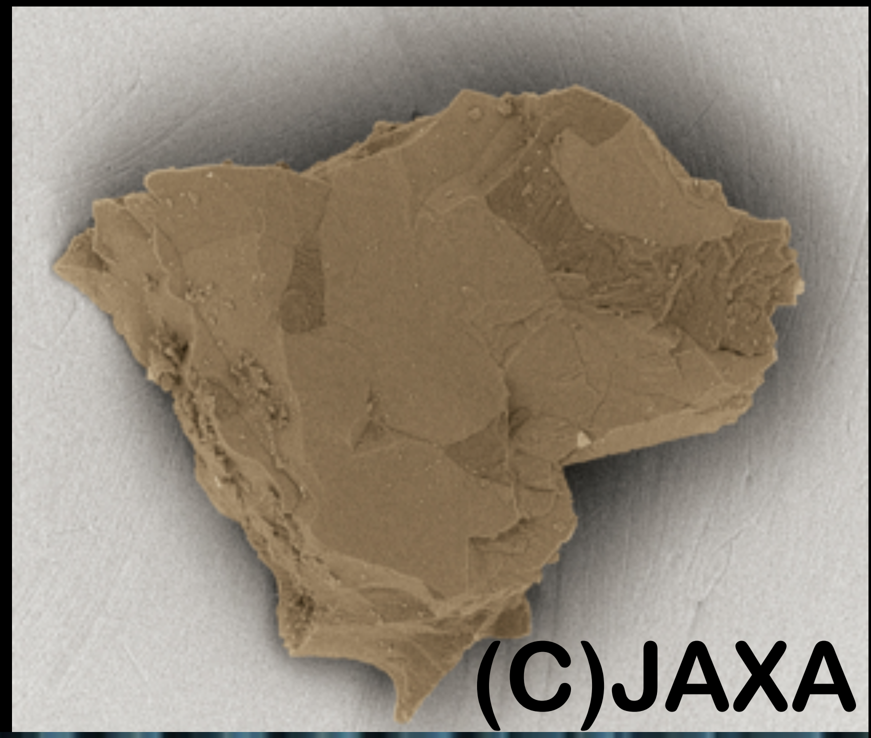
Ph.D in physics from Kyoto University, Japan in 1992
MU joined the Department of Earth Science and Astronomy, Univ. of Tokyo, and moved to the Institute of Space and Astronautical Science (ISAS), JAXA in 2009. His former occupations were the Head of Mission Instrument Technology Group, Director of ISAS Program office, and Chief Engineer of JAXA. MU moved to the Center for Planetary Science, Kobe University in 2016, and moved back to JAXA in 2019.
MU has served as a the Director of Astronomical Society of Japan,
and also serves as the Chair of Standing Space Agency Subcommittee, International Project/Programme Management Committee, (also vice-chair of Standing Space Agency Subcommittee, Knowledge Management Technical Committee).

MU's research interests include infrared astronomy, solar system science, scientific instrumentation and systems engineering in space development. MU has been involved in several space missions;

- ✓ AKARI (Infrared Astronomical Satellite),
- ✓ AKATSUKI (Venus orbiter)
- ✓ HISAKI (extreme-UV telescope in space)
- ✓ Recovered sample analysis of HAYABUSA.





Introduction

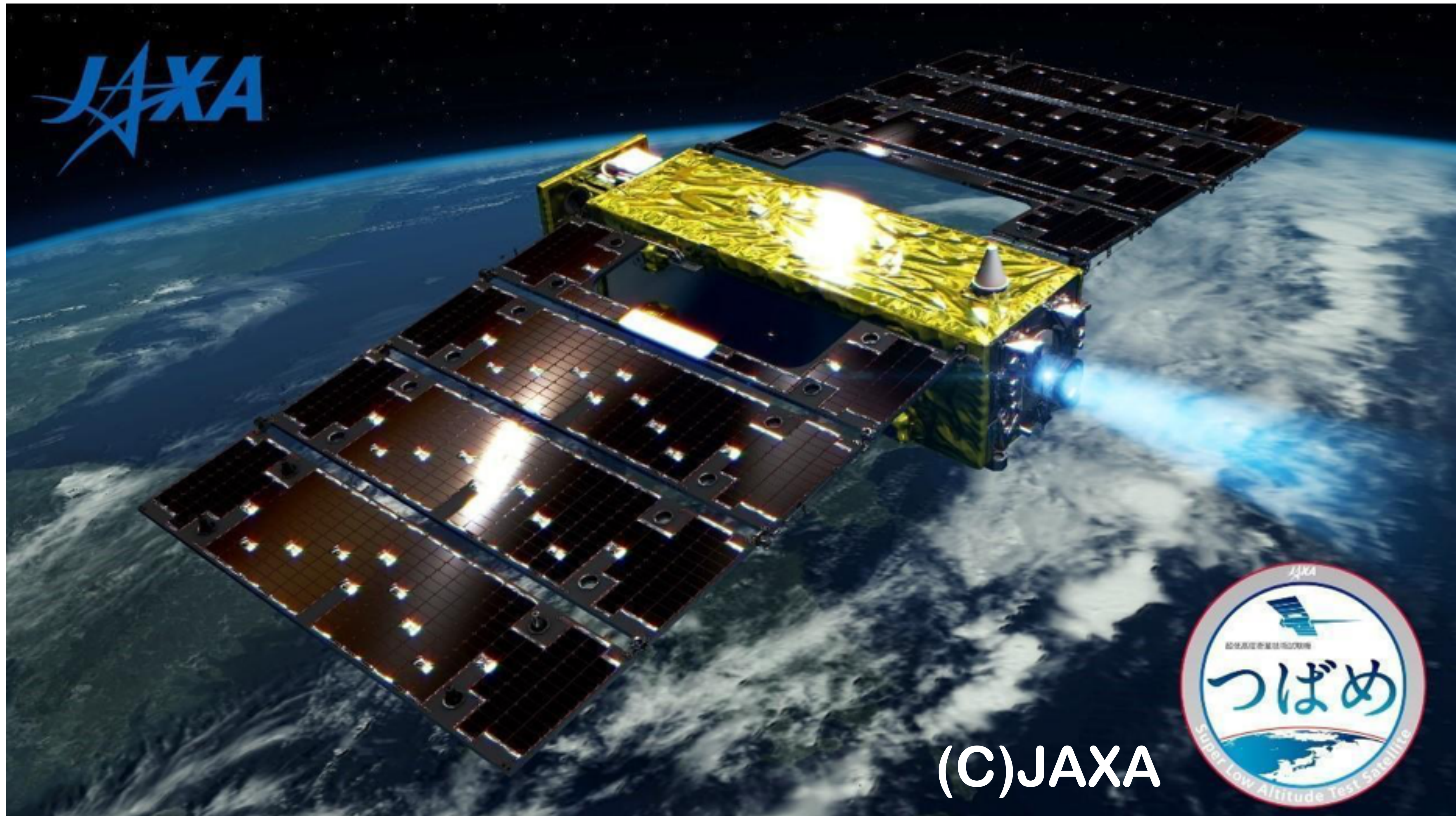
Where will your space career take you?

My talk today is not limited to space development.
This is a concept that can be defined in many fields of work, but it is useful in the way you think about the development of what we call systems.

In particular, I think that those of you who are listening to this talk today are thinking about creating and proposing missions (in 7th Mission Idea Contest for Deep Space Science and Exploration with micro/nano satellites). Today, I will focus on space science and deep space exploration. As I mentioned at the beginning, I believe that this content is useful for projects in a wide range of fields.

Introduction

In the title of my talk, I use the keyword "science operations”.
In space science and space exploration missions, the term "science operations" encompasses a very wide range of activities.
In space missions, “operation” refers to the operation of spacecraft and satellites,
while the word "operation" may remind you of surgical operations but in space missions, it refers to the operation of spacecraft and satellites.



Introduction

The term "science operations" does not just refer to how to operate a spacecraft, but includes all processes up to the creation of scientific results.

"Science operations" refers not only to how to control a spacecraft, but also to the entire process of creating scientific results: how to acquire the desired data, how to analyze it into a form that can be used by researchers, what kind of system is needed to do so, and what kind of team of researchers needs to be organized to utilize the results and bring them to fruition. It also includes how to publish the results. To use a term that is often used these days, mission design includes everything from mission development to outcomes in its scope.

Introduction

It may seem like a very tedious step to consider, but in many jobs, not just space science and exploration missions, grounding the design of the job from the development to the results obtained by the stakeholders is the key to a successful project or business.

The mission you are working on this time is relatively small in size. You will need to think with a lot of limitations. It is difficult to include so many things in your mission, so it would be good if you could first think carefully about the goal of the mission, then you can enjoy the "limitation".

Introduction

Some people may think of a mission that has been done in the past and want to do that kind of mission by themselves, or they may think of unusual techniques that they want to try it out. This must be very natural way at the beginning.

However, the most important thing is to clarify the objective and think about what is necessary to achieve it. From the perspective of creating results, it is not enough to simply create something and obtain some data, but it is important that it is properly linked to results.

Introduction

The purpose of the project can be either a scientific discovery or a technological challenge, but it is important that the purpose is clear and that the design is done properly to achieve the purpose. Even some large-scale missions have failed to produce sufficient results because of inadequate considerations of this aspect.

I will first introduce the importance of operations, and then introduce the concept of system design to realize the mission objectives. This is an introduction to systems engineering, a method often used in the space development process.

Importance of operations

When you think about mission design, you will notice that there are many necessary things and functional requirements standing side by side.

For example; two different actions or two different devices may be required to execute a single objective. However, the two or more actions required may be incompatible or exclusive.

If this problem is not considered at the beginning, a lot of preparation may end up in vain. It is not easy to put this much thought into a mission proposal, and the evaluators may not even realize it. However, it will be an important issue in the actual development of the missions.

Importance of operations

For example; the operation of communicating data to the ground station is often incompatible with observational operations or technical challenges. For communication, the antenna of the spacecraft needs to be pointed towards the Earth, but the instrument will often have other operational constraints. In general, it may not be possible to satisfy these two at the same time. This is also something to think about carefully.

Importance of operations

For this reason, it is important to consider the scheduling of the operations to a certain extent (not a instance), and to think about what kind of operations are actually needed at the beginning.

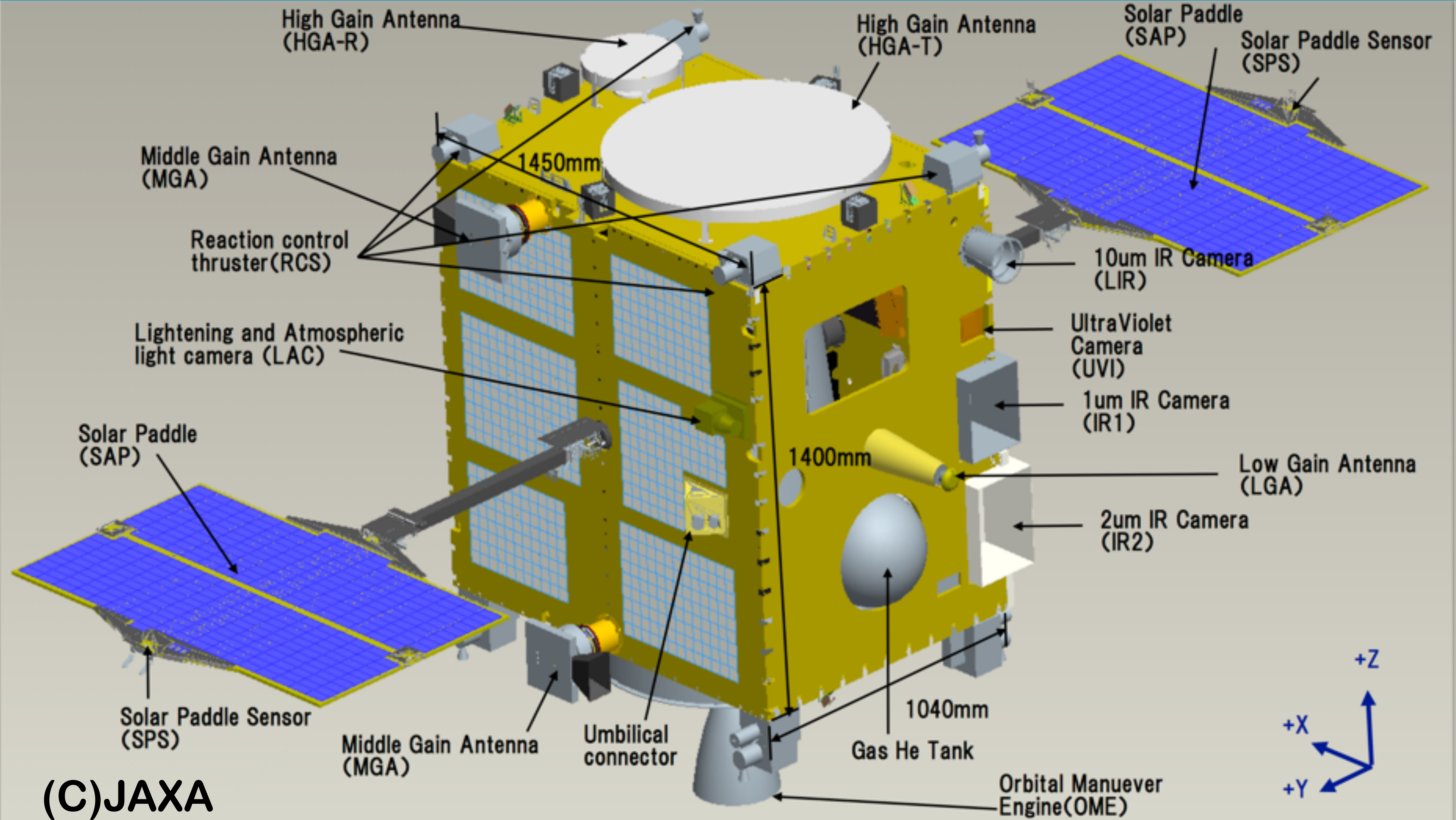
If there are actually conflicting requirements, it may be necessary to rethink the design or select the right functions. You will also be constrained by the size, weight, and development requirements of the mission as a whole. Therefore, I believe that you will face some challenges in the process of mission planning. In order to prepare for these challenges, it is important to consider the priorities of what is necessary to achieve the goals, starting with the most important issue.

Importance of operations

For example; we have a Japanese mission called "AKATSUKI", which is a Venus probe. This mission is equipped with five cameras. It was required to track the movement of the clouds in the Venusian atmosphere while observing Venus every two hours in order to solve the mystery of the super-rotation of the Venusian atmosphere, which is the major goal. It is truly a meteorological observation satellite on Venus.

In the AKATSUKI spacecraft, all five cameras are mounted fixed to the spacecraft. Similarly, the antennas are fixed to the spacecraft. Since the Earth is rarely in the orbital plane of AKATSUKI on Venus, observation of the Venusian atmosphere and communication to the Earth are incompatible. However, in order to deliver the minimum amount of imaging data calculated from the requirements, it was necessary to communicate with the ground station continuously for eight hours a day.

AKATSUKI Space craft



5 Cameras onboard AKATSUKI

IR1 λ= 0.9 1.01 μm
1024x1024 SiCCD

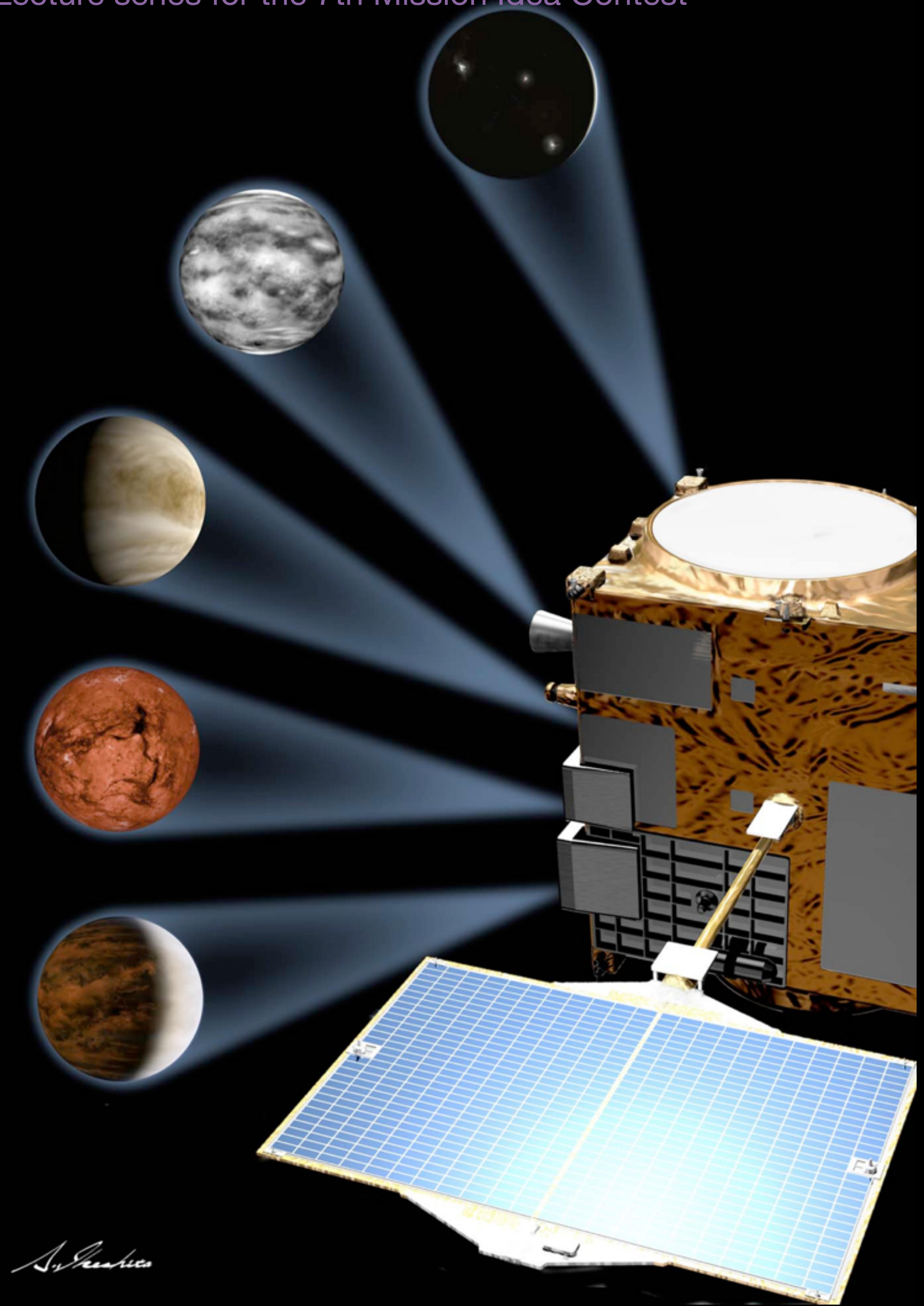
IR2 λ= 1.73, 2.26, 2.32 μm
(Venus atmosphere.),
2.02 μm (CO_2), 1.65 μm (IPD)
1024x1024 PtSi

UVI λ= 280, 365 nm
1024x1024 UV intesified SiCCD

LIR λ= 8-12 μm
240x320 micro bolometer array

LAC λ= 777, 551, 558 nm
8x8 Av. photo-diode (10kHz sampling)

DE & USO



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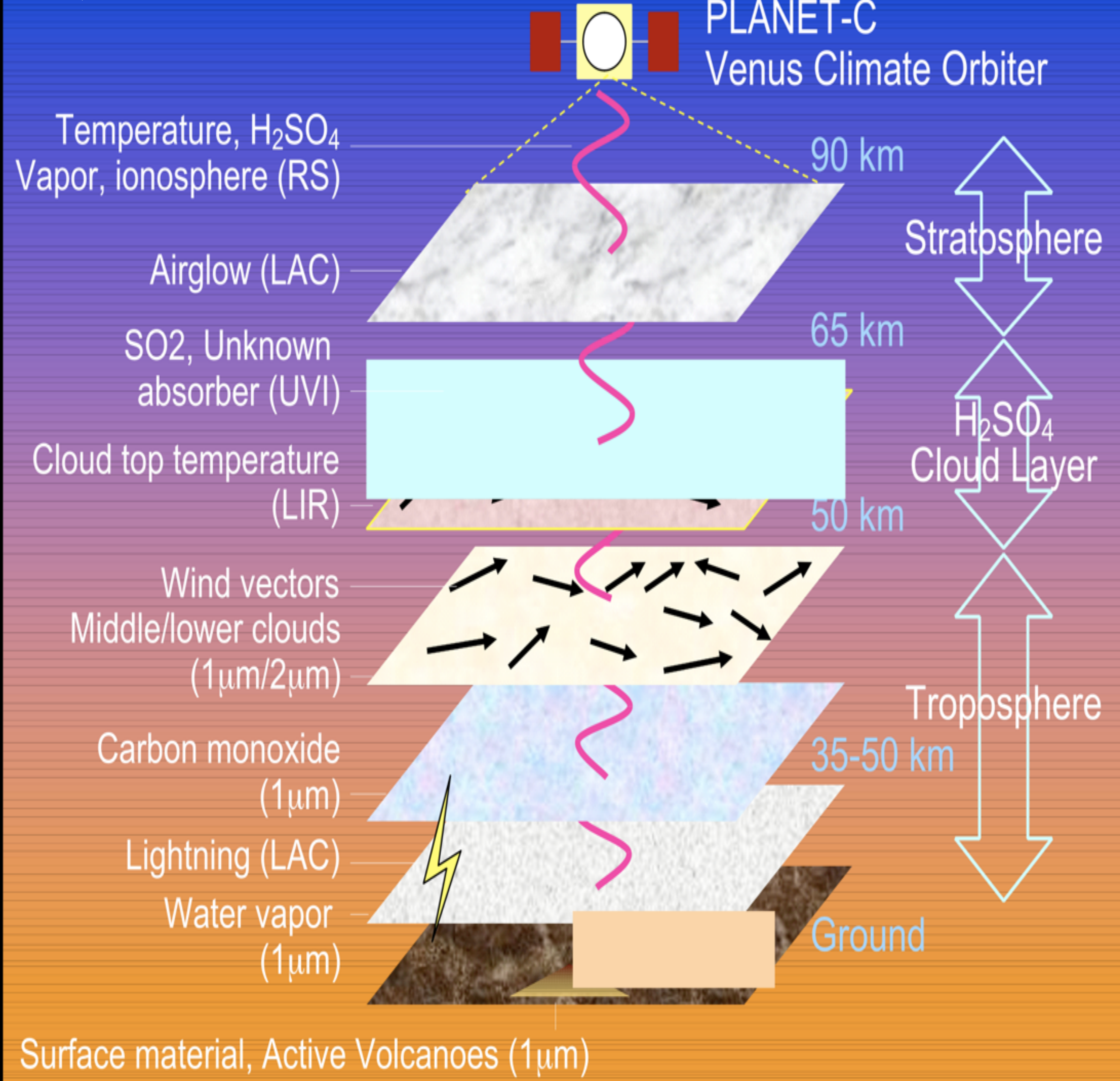
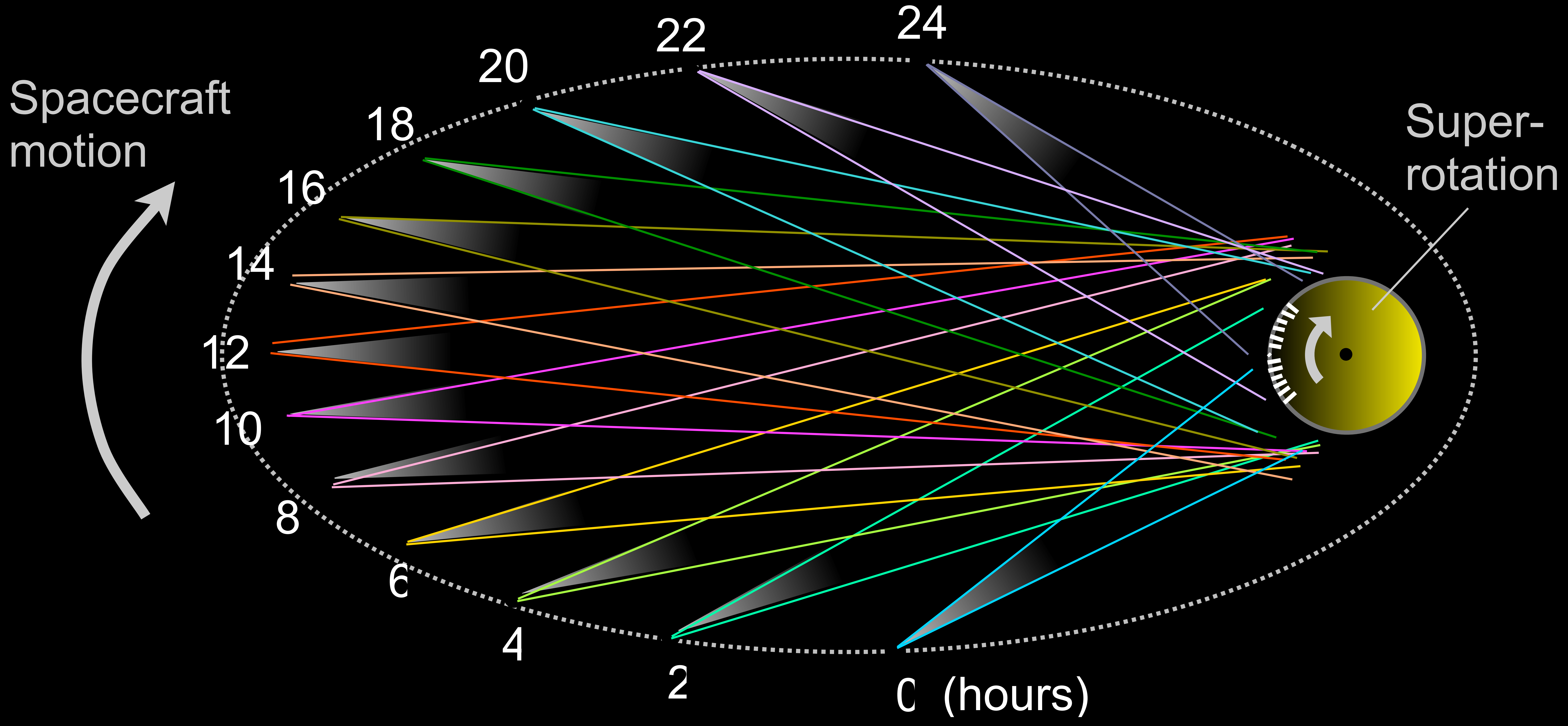
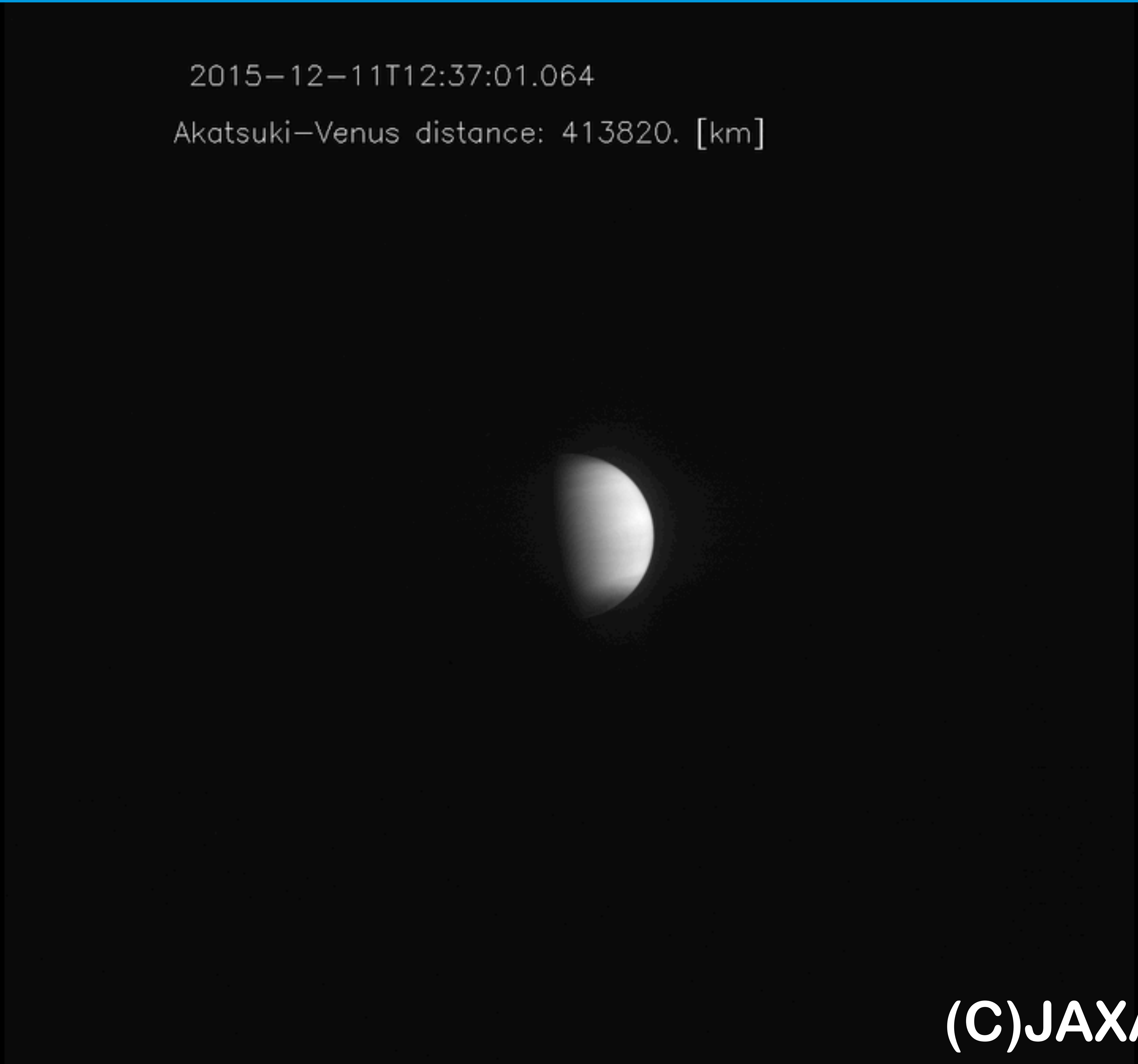


Viewed from the north pole



Optimization for detecting small deviations of atmospheric motions from the background flow

Venus images taken from different altitude (AKATSUKI)



Importance of operations

Since the spacecraft is far away from the Earth, it may take up to 30 minutes for the radio wave to travel back and forth, depending on the distance from the Earth, and the single sequence of observations itself takes about 20 minutes. In other words, there will be a dead time of about 45 minutes before the first connection is made. The implication is that if we carry out observations every two hours, including the time required to change the attitude of the spacecraft, there will be a dead time of more than one hour every two hours, which means that we will be able to transmit less than half the amount of data we had planned. This meant that we had to make a tough choice: either give up observations during the communication time, or prioritize observations by reducing the communication time. As a result, it became difficult to acquire and send continuous data every two hours, which was the original purpose of the mission.

Importance of operations

The design of the AKATSUKI spacecraft had all the necessary equipment for the observational purpose, and the spacecraft as a whole had sufficient functions and performance to meet the individual requirements. However, because we did not sufficiently consider how to allocate the instruments and how to operate them from the standpoint of actual operation, the instruments were not able to demonstrate their full potential.

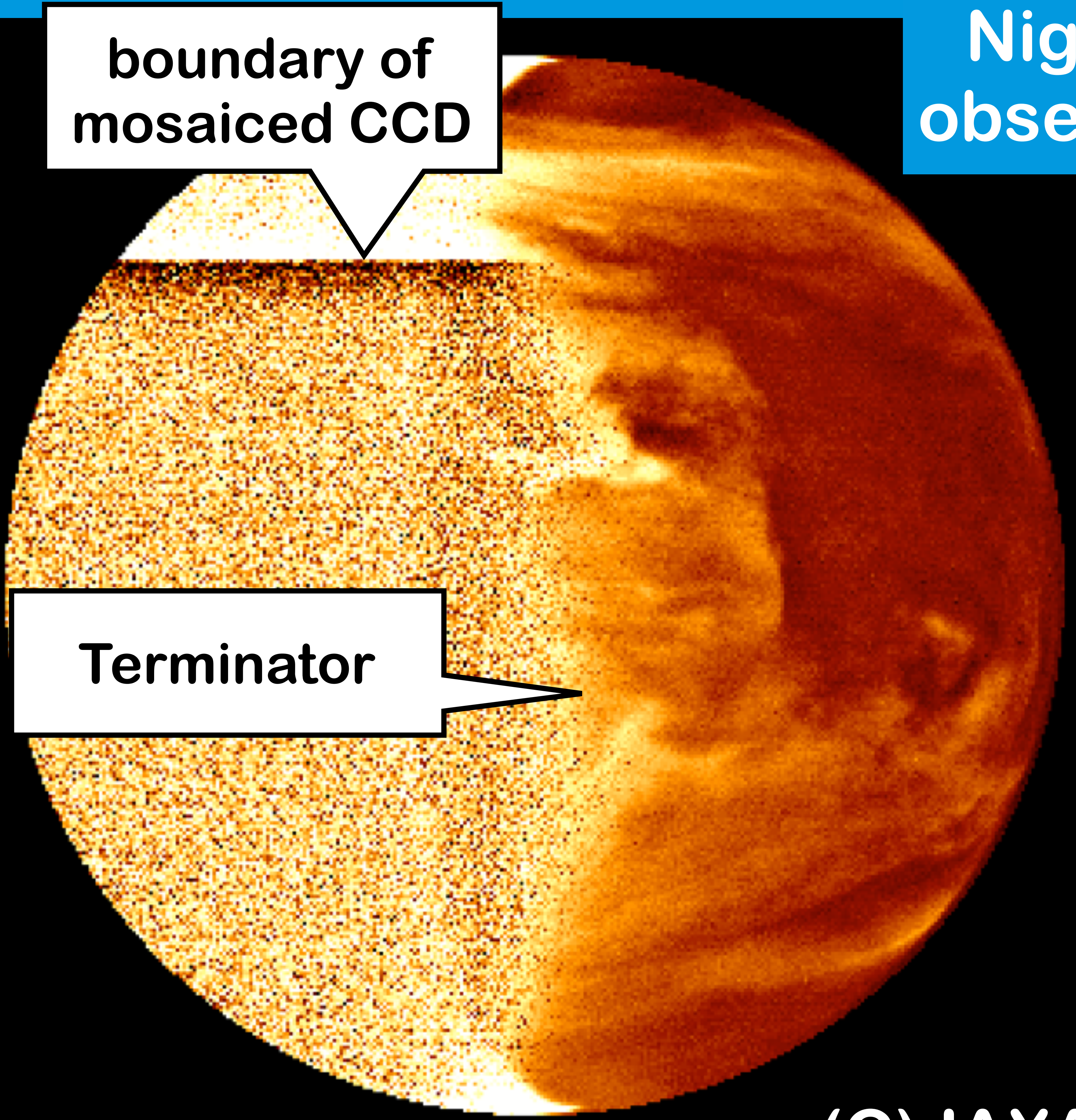
The mission you are about to consider is a very small spacecraft compared to AKATSUKI. You will be faced with a tough selection process under very limited boundary conditions, and you will have to consider first whether it is feasible, including the operation.

Importance of operations

The AKATSUKI spacecraft produced the world's first meteorological observation of Venus being able to capture many unknown phenomena and produce many scientific results; but the success of the mission could have been much greater if the initial consideration had been sufficient.
For example; if the antennas could have been operated with a certain degree of freedom, some of the problems could have been solved. However, due to the limited weight and power available on the spacecraft, we would have had to give up some of the cameras in exchange for the resources required for this operation. However, this would have led to greater results. As you can see, it is very important to think about the actual operation at the beginning of the mission design.

Scientific Highlight of AKATSUKI Observations of IR2 (2um camera)

Night side observations



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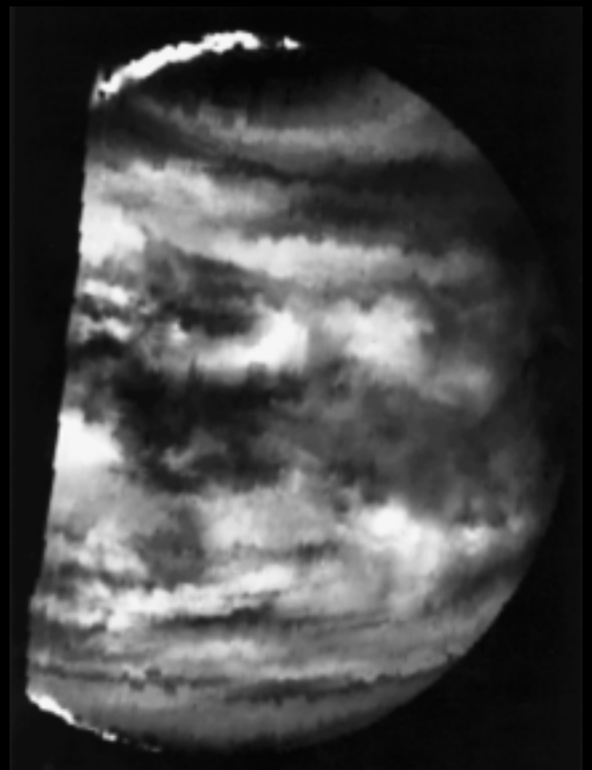

Image by Galileo NIMS (2.3μm)
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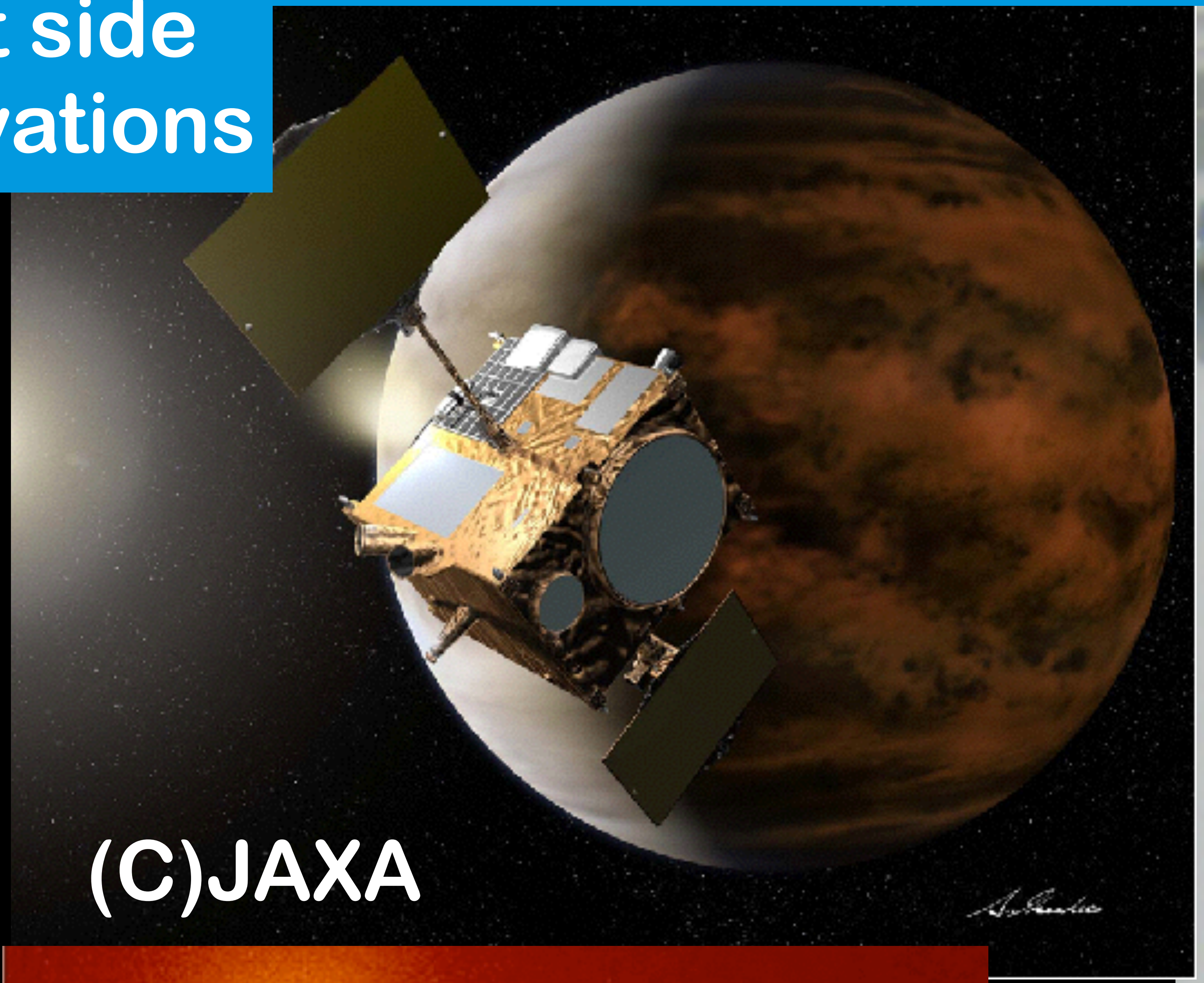

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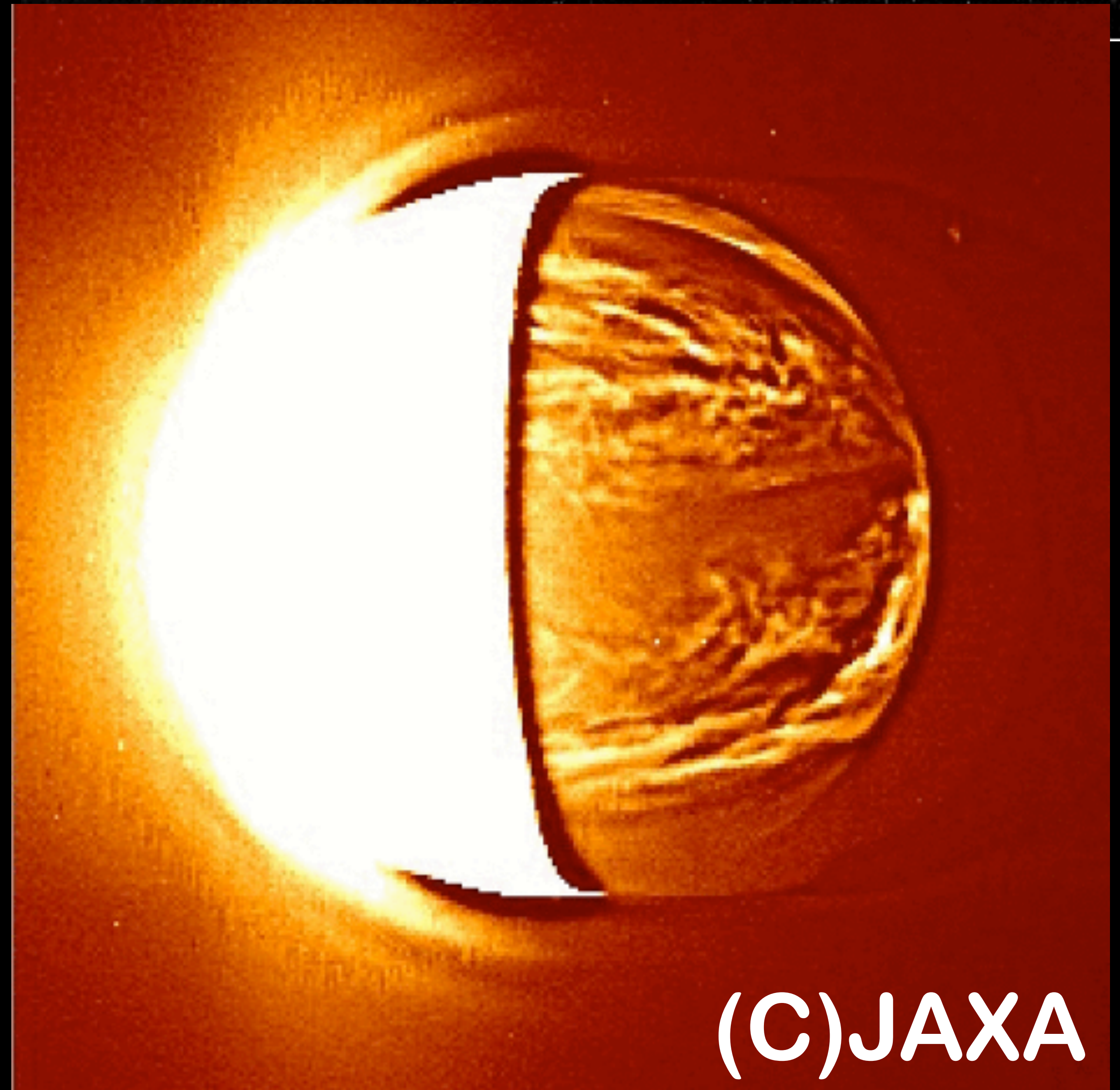

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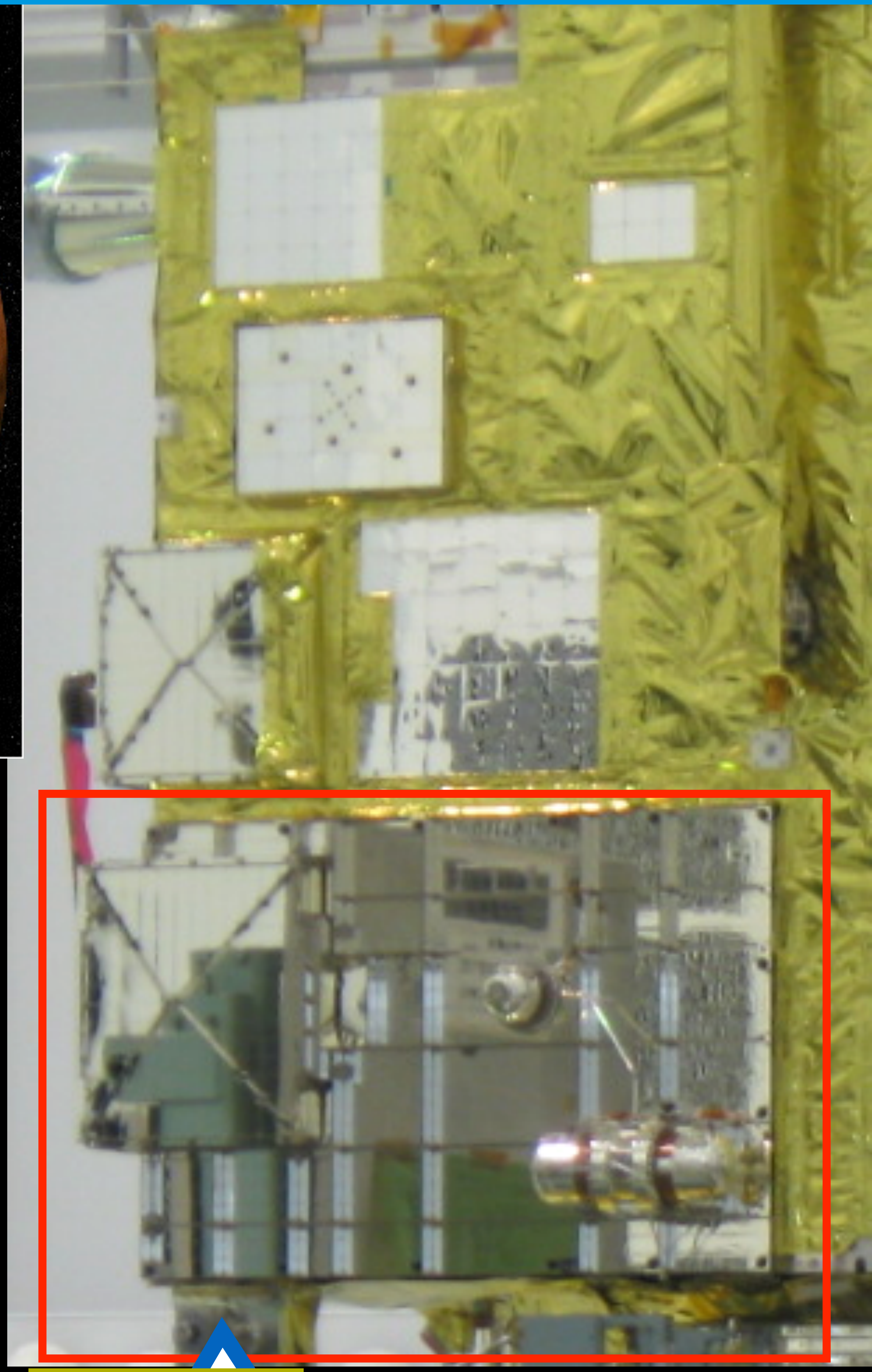

IR2

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Scientific Highlight of AKATSUKI Observations of IR2 (2um camera)

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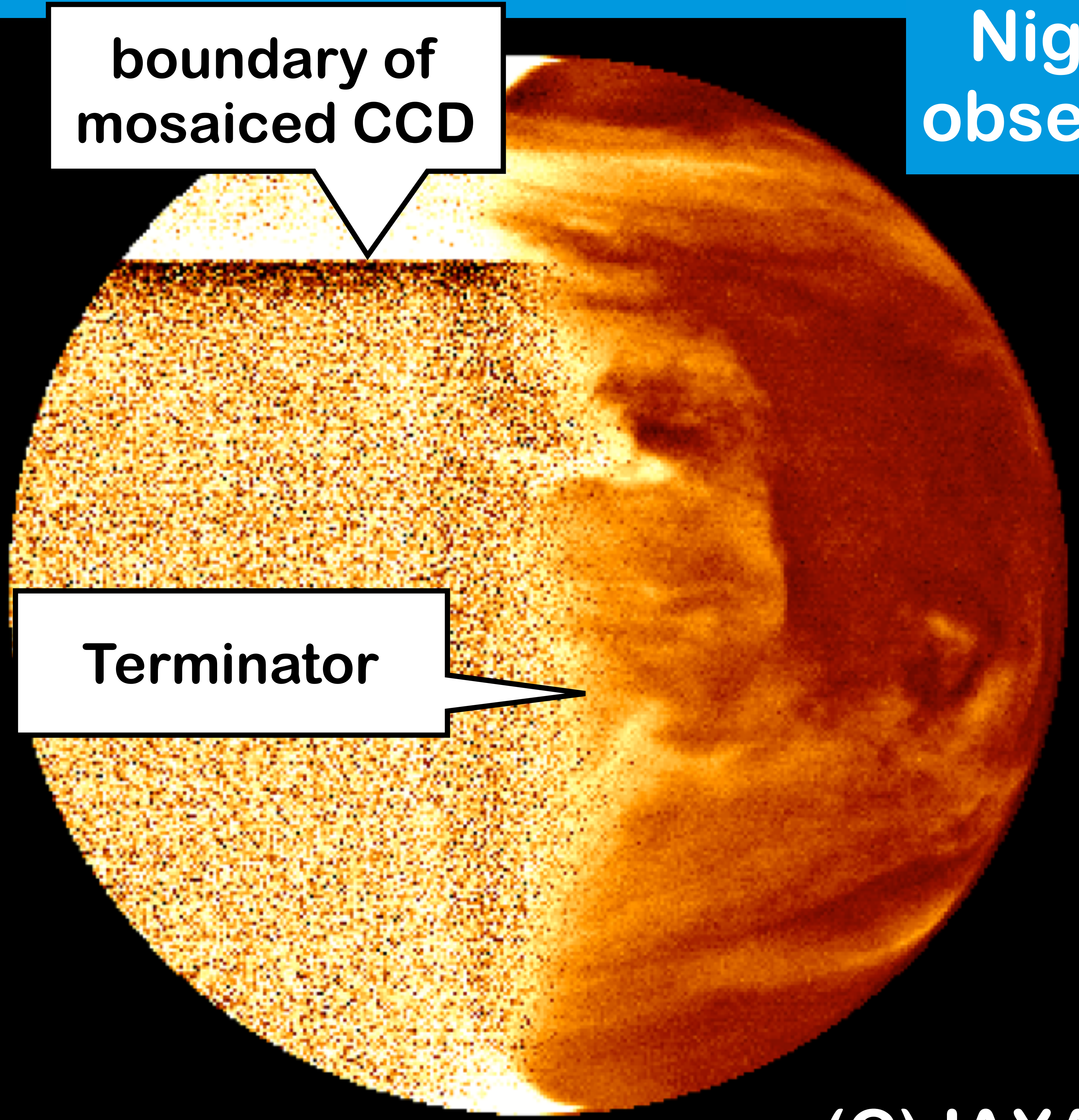

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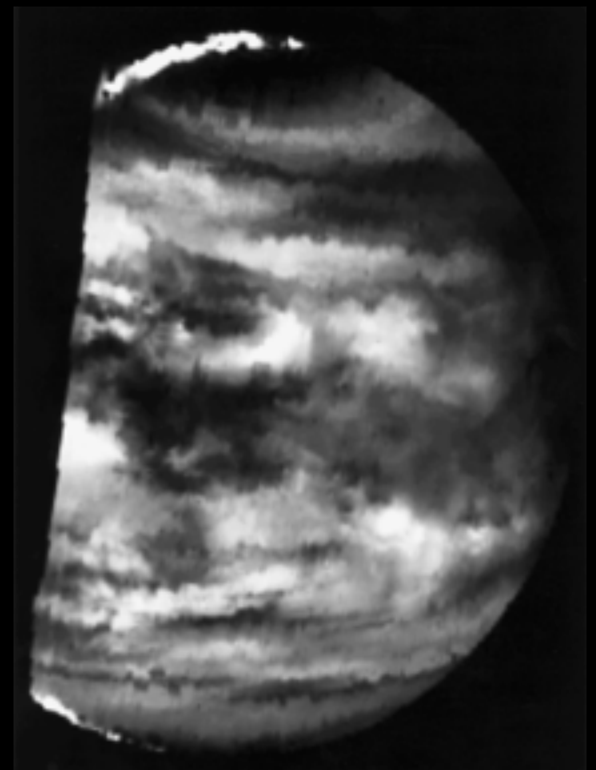

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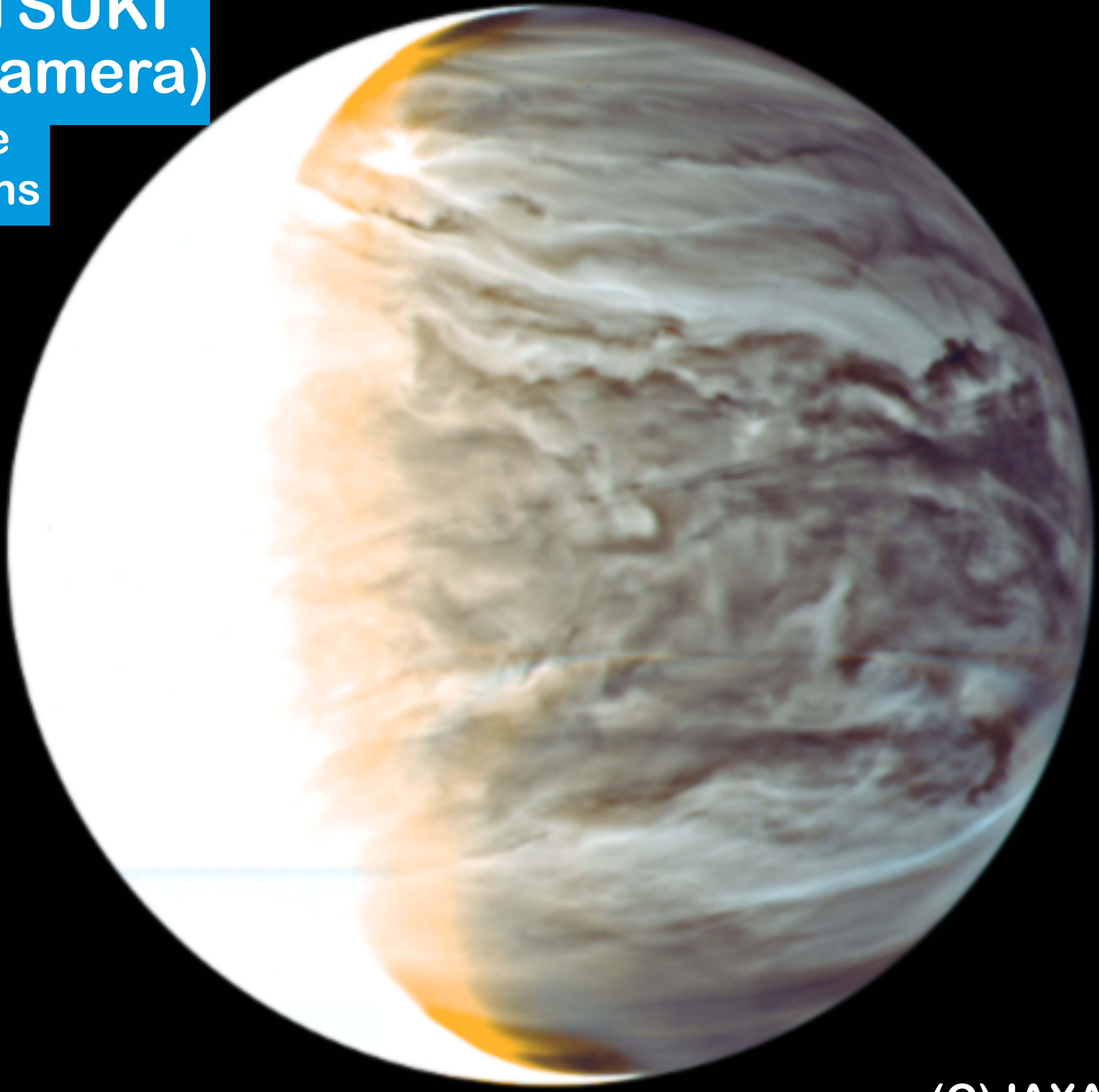

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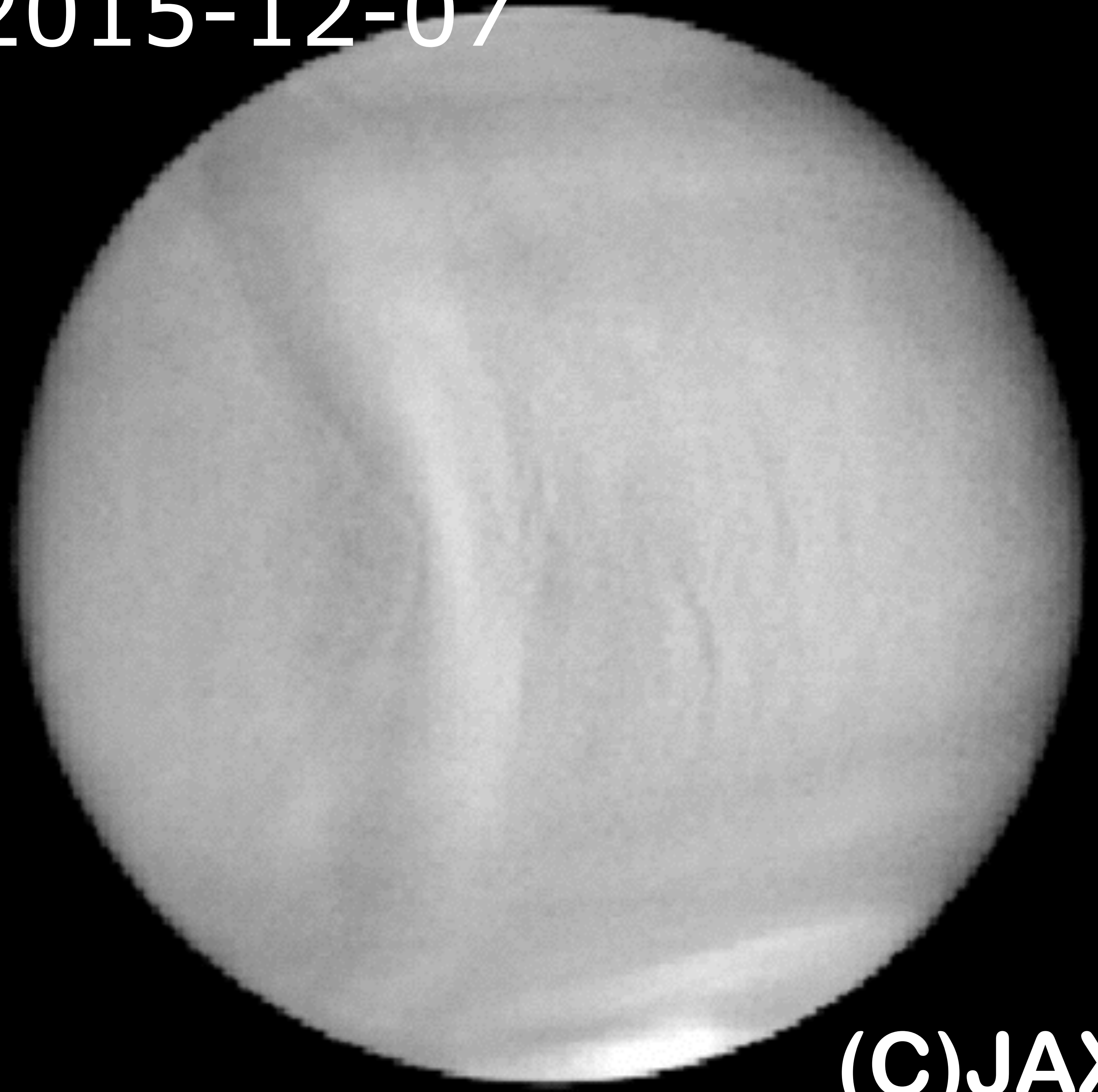
Scientific Highlight of AKATSUKI
Observations of LIR (10um camera)

- The first discovery of a bow-shaped structure
- Highest temperature at around the south polar region
- Detection of filamentary structure of lower temperature area

2015-12-07



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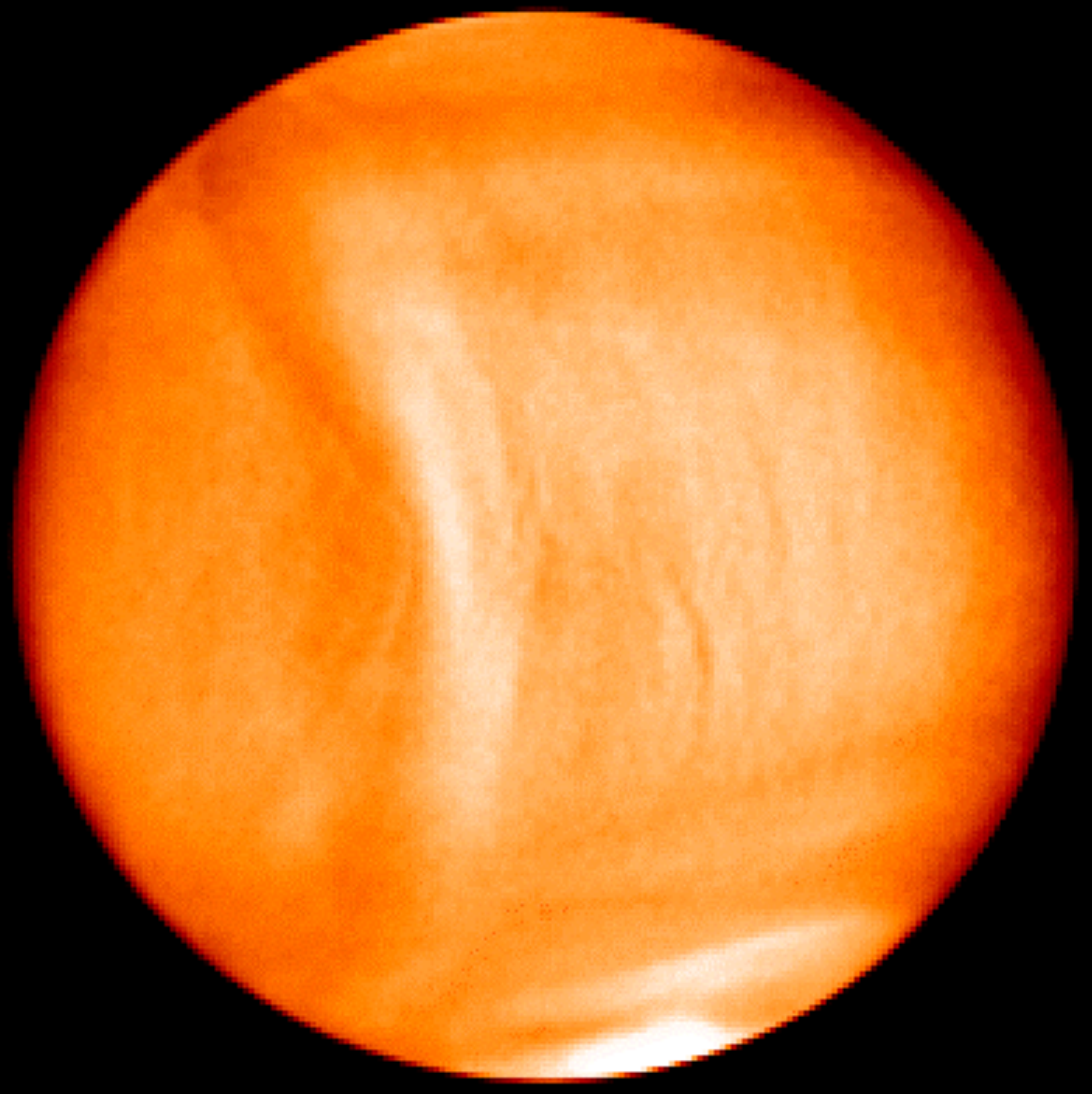

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Scientific Highlight of AKATSUKI Observations of LIR (10um camera)

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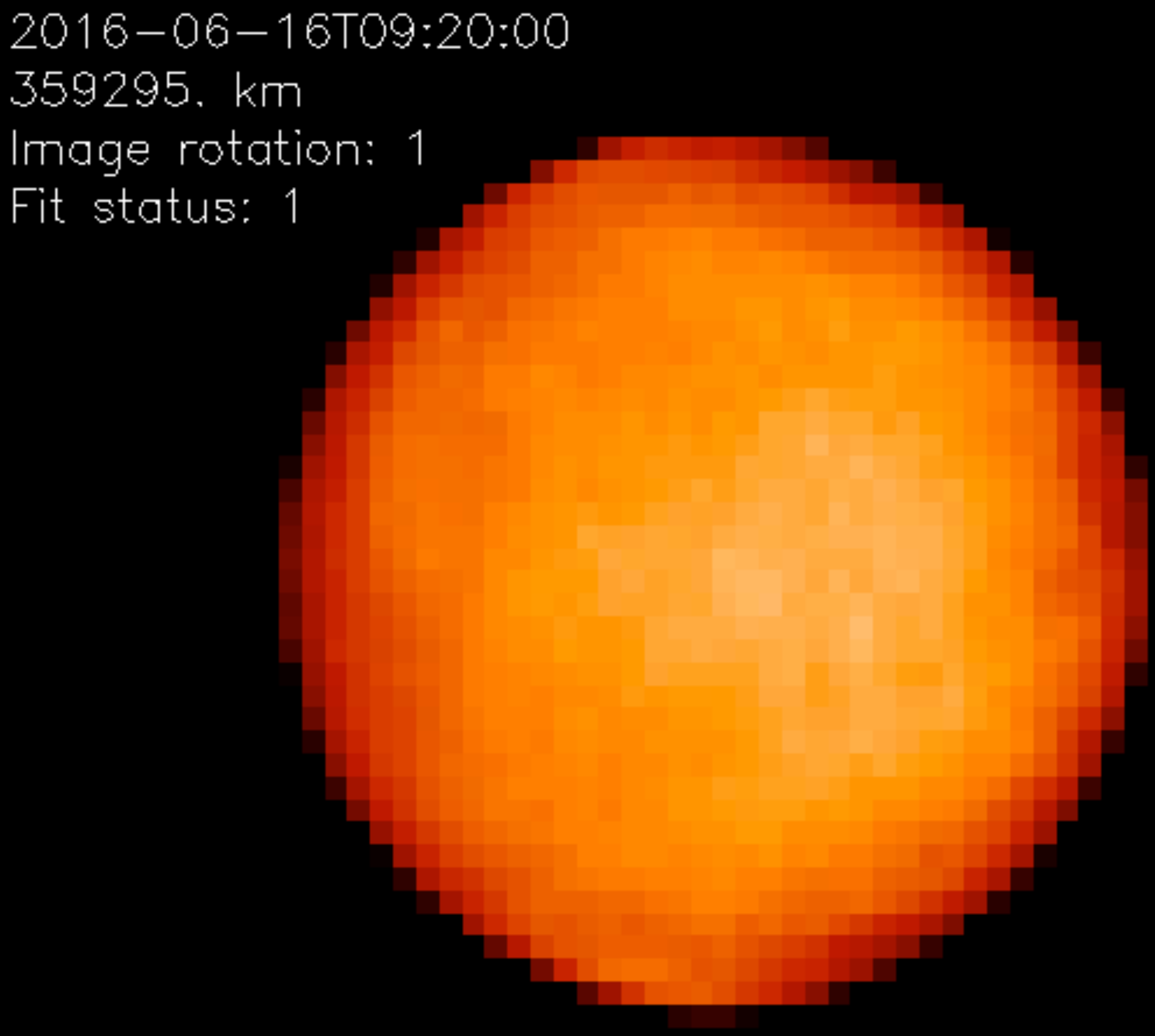


Introduction of
Systems engineering approach

- Mission design and systems engineering
- Project Planning
- Objectives – Requirements - Solutions
- Why do we need requirements?
- Properties of Requirements
- Trade-off
- Requirements & Design Drivers
- Mission Definition
- Mission Phases

Introduction of Systems engineering approach

- When you fix a mission design
  - Design of the spacecraft shall be feasible
  - To confirm the readiness of the mission.
    - Conceptual design work is needed including:
      - Mission operation.
      - Verification plan of the requirements of the mission.
- Systems engineering must be very important in these early phases of mission designing.

What is “system”, and “Systems Engineering”

“The objective of systems engineering is to see to it that the system is designed, built, and operated so that it accomplishes its purpose in the most cost-effective way possible, considering performance, cost, schedule and risk.”

NASA Systems Engineering Handbook SP6105

Systems Engineering

- ✓ Systems engineering is a methodical, disciplined approach for the design, realization, technical management, operations, and retirement of a system.
  - ✓ A “system” is a collection of different elements that together produce results not obtainable by the elements alone.
  - ✓ Elements can include people, hardware, software, facilities, policies and documents.
  - ✓ All elements required to produce system level results.
  - ✓ Systems engineering is the art and science of developing an operable system capable of meeting requirements within imposed constraints.
  - ✓ Not dominated by the perspective of a single discipline.
  - ✓ The responsibility of engineers, scientists, and managers working together.

Mission design

Project Planning

1. Purpose and objectives of the project:

- ✓ a. Key questions to be answered
- ✓ b. Key technical performance parameters
- ✓ c. Technical and programmatic constraints

2. Technology availability and development needs:

- ✓ a. Potential cost and schedule drivers

3. Potential cost class.

4. Ability and need to re-use existing equipment/products.

5. Availability and need for human resources, skills, technical facilities.

6. Risk assessment:

- ✓ a. Risk management and mitigation actions

7. Development approach:

- ✓ a. Result from above considerations

Objectives – Requirements - Solutions

Objective is the high level motivation:

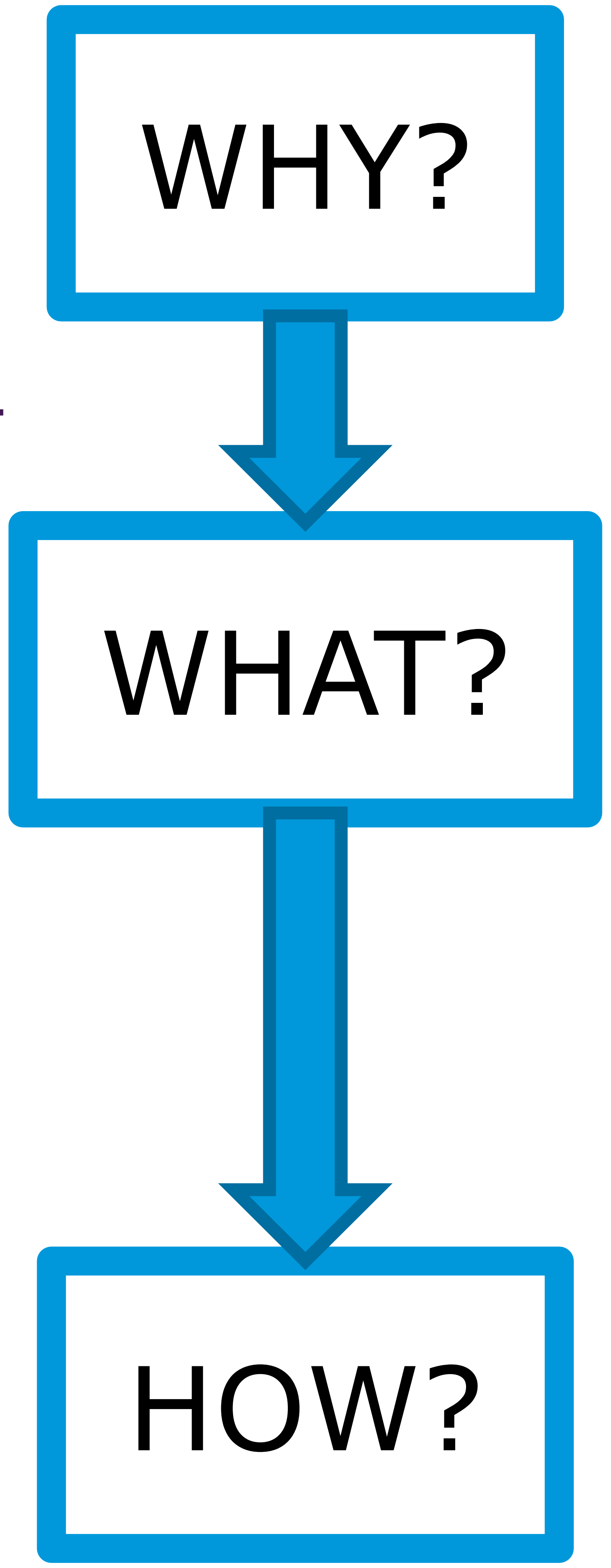
- ✓ Which scientific question/application purpose shall the project address and what answer is sought.

Requirement is the translation of this objective into verifiable statements of what is needed to achieve the objective:

- ✓ Have several levels of detail.
- ✓ Are traceable, all the way back to the top level.
- ✓ Include quantities.

Solution is the response to the all requirements:

- ✓ There can be several solutions meeting requirements.
- ✓ Non-compliance needs to be negotiated.



Mission Objectives

Science objectives: Objectives should ...

- ✓ a. Respond to important scientific questions or topics.
- ✓ b. State why a space mission is needed clearly (no other approach?).
- ✓ c. Be appealing:
  - ✓ to General public
  - ✓ to Science community

Application objective: Objectives should ...

- ✓ a. Serve an important need of the general public – provide benefits!
- ✓ b. State the unique contribution from space (why do you need observations in space?).

Why do we need requirements?
Very important process!!

1. To provide motivation and focus to the project.
   - ✓ a. Communicate to others what shall be achieved.
2. Requirements shall:
   - ✓ a. Answer the WHY?
   - ✓ b. By specifying the WHAT?
   - ✓ c. And not addressing the HOW?
3. To identify the trade-off for the best solution.
4. Place priority on possible solutions/options.
5. Priority helps resolve …
   - ✓ a. Conflicting requirements.
   - ✓ b. De-scope paths.
6. Provide specifications to engineering and lower level subsystems.

Properties of Requirements

- ✓ 1. Mission statement: captures the objectives and measurements required in a single sentence.
- ✓ 2. Requirements: formal statements expressing what is needed to fulfill the mission objectives.
- ✓ 3. Requirements shall: be product related, not process related.
- ✓ 4. Clear requirements are key to good design
- ✓ 5. Requirements are hierarchical: lower level system requirements shall come from higher level mission requirements.

Requirements – Examples

1. Good Examples:

- ✓ a. The mission shall provide a measurement of the parameter constant with an accuracy better than 10^{-3}
- ✓ b. The mission shall allow scanning of the sky with an angular rate of 10 arcmin/s around an axis of rotation which is 90°±2.5° away from the Sun direction.
- ✓ c. The mission shall have a nominal in-orbit duration of 3 years.

2. Bad Examples:

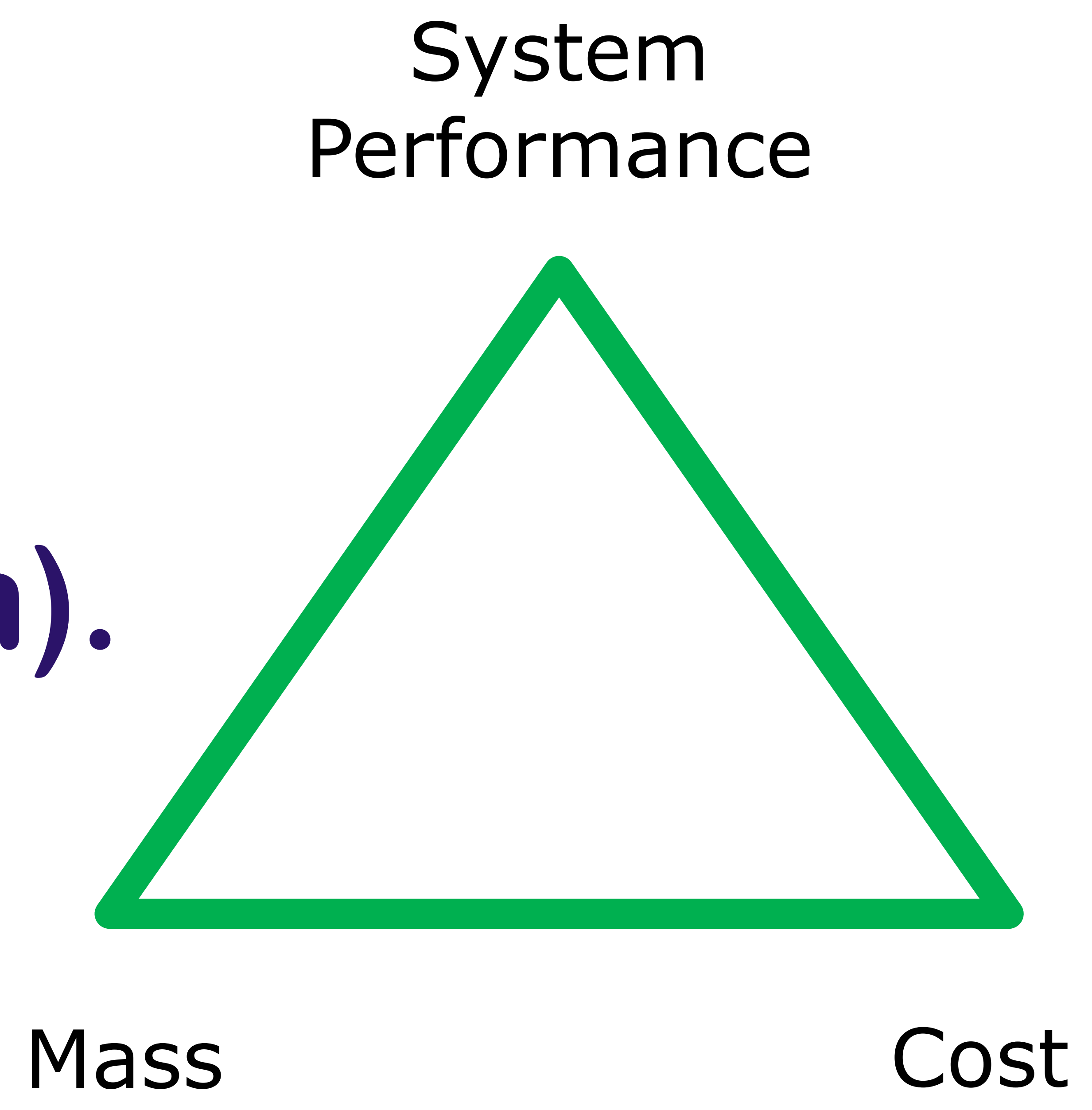
- ✓ a. The system design shall maximize the spectral resolution or scientific output.
- ✓ b. The mass shall be as low as possible

Trade-off studies

1. Trade-off allows exploring alternative solutions to a baseline.

2. The parameter space needs to be prepared, and an evaluation criterion shall be established using requirements.

3. Most common criteria: mass, cost (several system properties can be translated into them).



Requirements & Design Drivers

- 1. Identification of design drivers is the result of requirement analysis.
  - a. First iteration during definition of mission concept.
- 2. Design drivers constrain flexibility of system design (there should be as few as possible)!
- 3. Classify the requirements: unavoidable – negotiable.
- 4. Typical (expected) unavoidable design drivers:
  - a. Mission profile.
  - b. Communications.
  - c. Power generation.
- 5. Negotiable (examples):
  - a. Planning of telemetry downlink.
  - b. Operations constraints.

Mission Definition

1. "The art and science of developing an operable system capable of meeting mission requirements **within imposed constraints** including mass, cost and schedule."
2. Satisfy in a (near-)optimal manner all the requirements.
3. Requires trade-offs involving diverse systems and disciplines:
   - ✓ Propulsion, power, communications, orbital dynamics, thermal, structure, mechanisms, navigation, control, aero-thermo-dynamics, etc.
4. You need to identify what the important parameters are and how they are related!
5. Define and compare a small number of different possible scenarios.
6. Choose **the most promising option** and perform a more detailed design, including space & ground segments, operations, cost and risk.

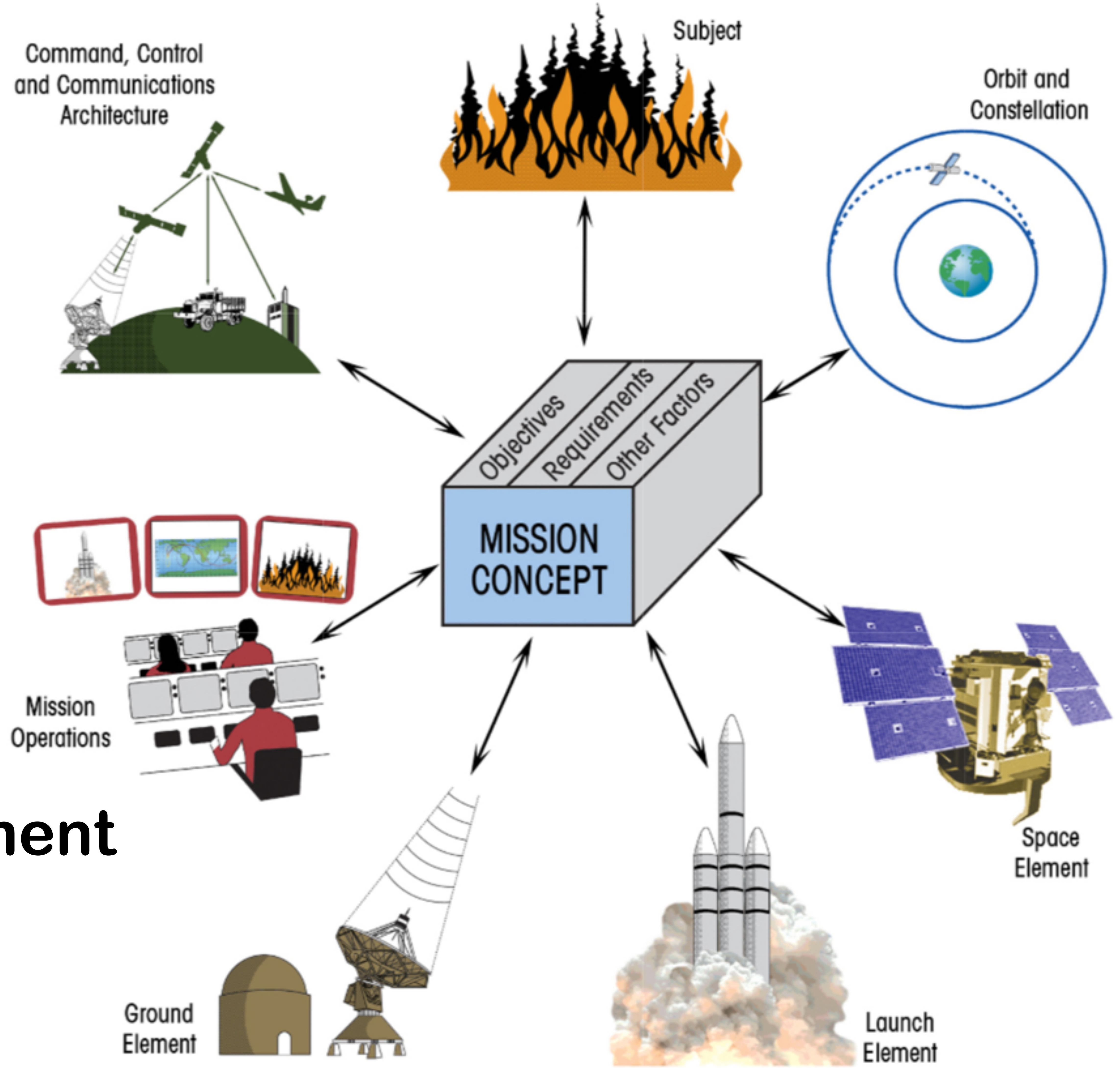
System Design / End - to - End view

Initial Study Phase

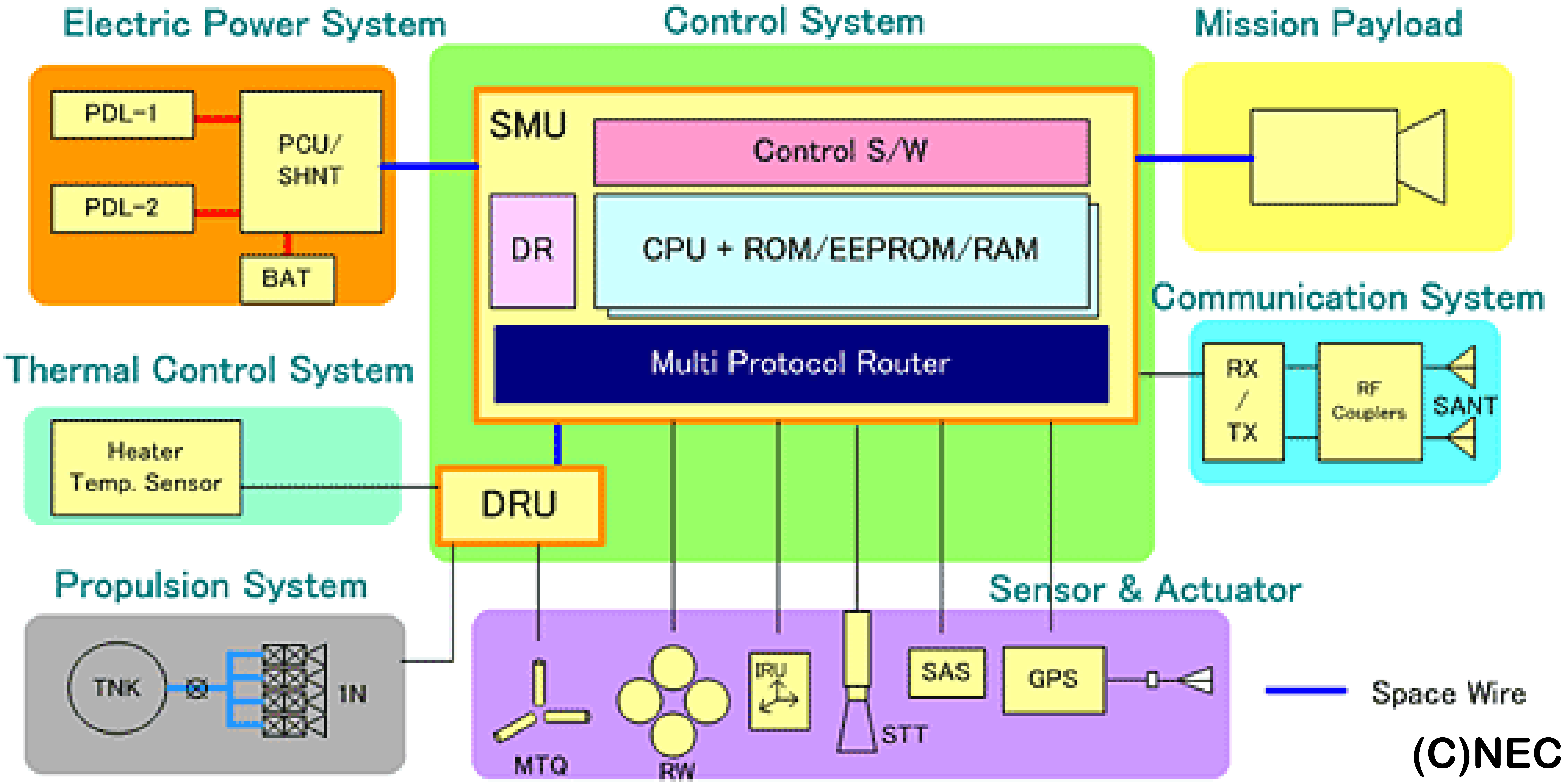
- Analysis of Mission Objectives
- Analysis of Mission Constraints
- Definition of Science Requirements
- Definition of Mission Architecture
- Definition of payload / performance
- Analysis of Environment
- Iteration / Trade-off phase
- Cost, Risk, Schedule, Technology Development

Goal

- feasible mission profile
- satisfying requirements and constraints



A typical satellite system (NEXTAR)



From mission definition into system definition

Generally speaking, the number of missions definition could apply to the mission objective.

System definition has the same situation as above.

- ✓ Various choices of system definition to satisfy the mission (science) objectives may exist, however the most feasible(*) one is unique. Importance of "Best compromise"

*feasibility is usually on the balance of budget, necessary resource, and risks.

[Exercise just for training]

Suppose you were requested to measure the mass of our planet:

- ✓ You could find many approaches to do so.
  - ✓ Your ideal choice is the best and most effective method..

From mission definition into system definition

- We have to select the "best compromised" definition, after the cascades of "trade-off studies" - starting from the purpose!

- "Trade-off studies" shall be recorded in detail even for very simple matters, because we frequently need to go back to modify (reconsider) the definition of the previous phase in case we find some difficulties to realize the full spacecraft system.

* Priority and traceability of the requirements are highly important.

- Concurrent Design Process is mostly helpful in the early phase, to check the feasibility of the mission design within the given resource budget.

Systems engineering is an aid to the study.

- ✓ The important thing about systems engineering is that it moves from the big goals to the individual objectives, then to the mission requirements, then to the system requirements, so on.
- ✓ During this in-depth study, there are generally countless options.
- ✓ Therefore, it is very useful to record the perspective from which the choices were made, including the trade-offs made.
- ✓ This is because in many cases the boundary conditions will not be satisfied when you proceed to the actual concrete mission design.

Systems engineering is an aid to the study.

- ✓ In such cases, if you can look backward to see from which part of the higher-level requirements for a certain part of the mission design are coming, you can know what will happen if you cut off that element.

- ✓ In general, mission studies often fail to meet the given boundary conditions for concrete design, so a process of iteration is necessary to go back to the higher-level requirements through hierarchical importance. This cyclic process will make the mission much smarter.

Systems engineering is an aid to the study. Here are some things to keep in your mind

- ✓ Systems engineering is not a magic box. It doesn't give you any mission ideas.
- ✓ It is a set of procedures that guides you through the process of fleshing out a good idea, and the most important aspect of all is whether or not it is a good idea.
- ✓ When you follow systems engineering, you often feel that you have done a good job, and that you have done a good job even if the ideas and trade-offs are not well thought out, and you often tend to conform to the guide more than necessary.

Please remember that good ideas lead to good missions!

Enjoy the hard work of the preparation!