月の基準座標系の国際調整

一般財団法人宇宙システム開発利用推進機構
衛星測位事業本部 利用開拓部長
博士(工学) 浅里幸起

国際標準提案先: ISO/TC 20/SC 14委員会

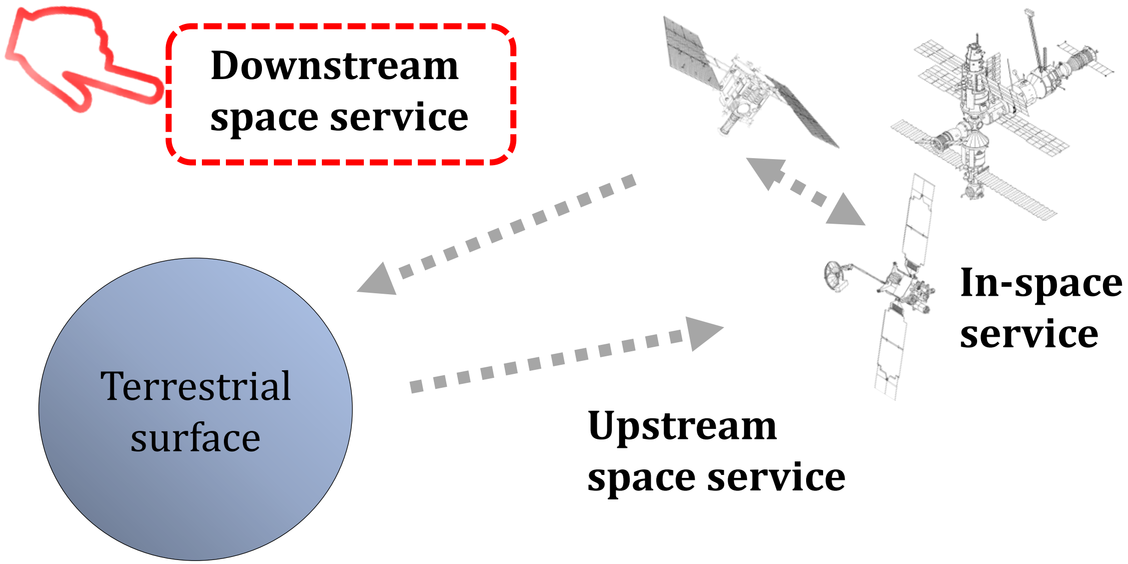
Space systems and operations

Reference ↑	Title	
ISO/TC 20/SC 14/AG 1	Chair's Advisory Group	
ISO/TC 20/SC 14/AG 2	Terminology task force	技術用語タスクフォース
ISO/TC 20/SC 14/AG 3	STRAG - Reference Architecture Advisory Group	参照アーキテクチャー
ISO/TC 20/SC 14/WG 1	Design engineering and production	設計と製造
ISO/TC 20/SC 14/WG 2	System requirements, verification and validation, interfaces, integration, and test	システム要求、検査・検証、インタフェース、統合、試験
ISO/TC 20/SC 14/WG 3	Operations and support systems	運用と支援システム
ISO/TC 20/SC 14/WG 4	Space environment (natural and artificial)	宇宙環境
ISO/TC 20/SC 14/WG 5	Space System Program Management and Quality	宇宙システムのプログラム管理と品質
ISO/TC 20/SC 14/WG 6	Materials and processes	材料とプロセス
ISO/TC 20/SC 14/WG 7	Orbital Debris Working Group	宇宙デブリ
ISO/TC 20/SC 14/WG 8	Downstream space services and space-based applications	**宇宙利用サービス**

宇宙システム「ダウンストリーム」定義

Service	Location	
	Server	Client
Downstream space service	Space	Terrestrial
Upstream space service	Terrestrial	Space
In-space service	Space	Space

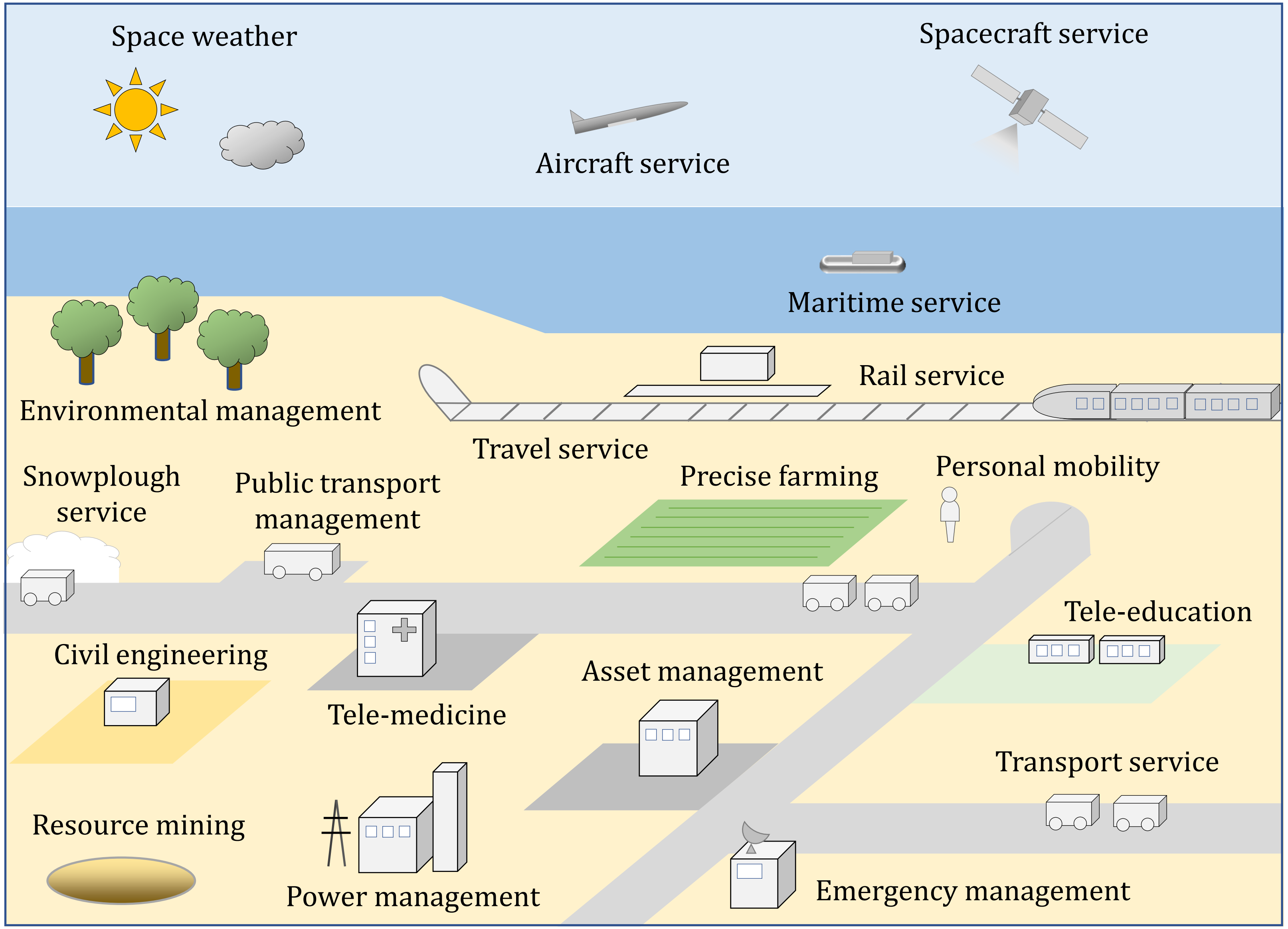
In this document,
terrestrial is an antonym of celestial and includes land, maritime, aeronautical, and near space which is close to the surface.



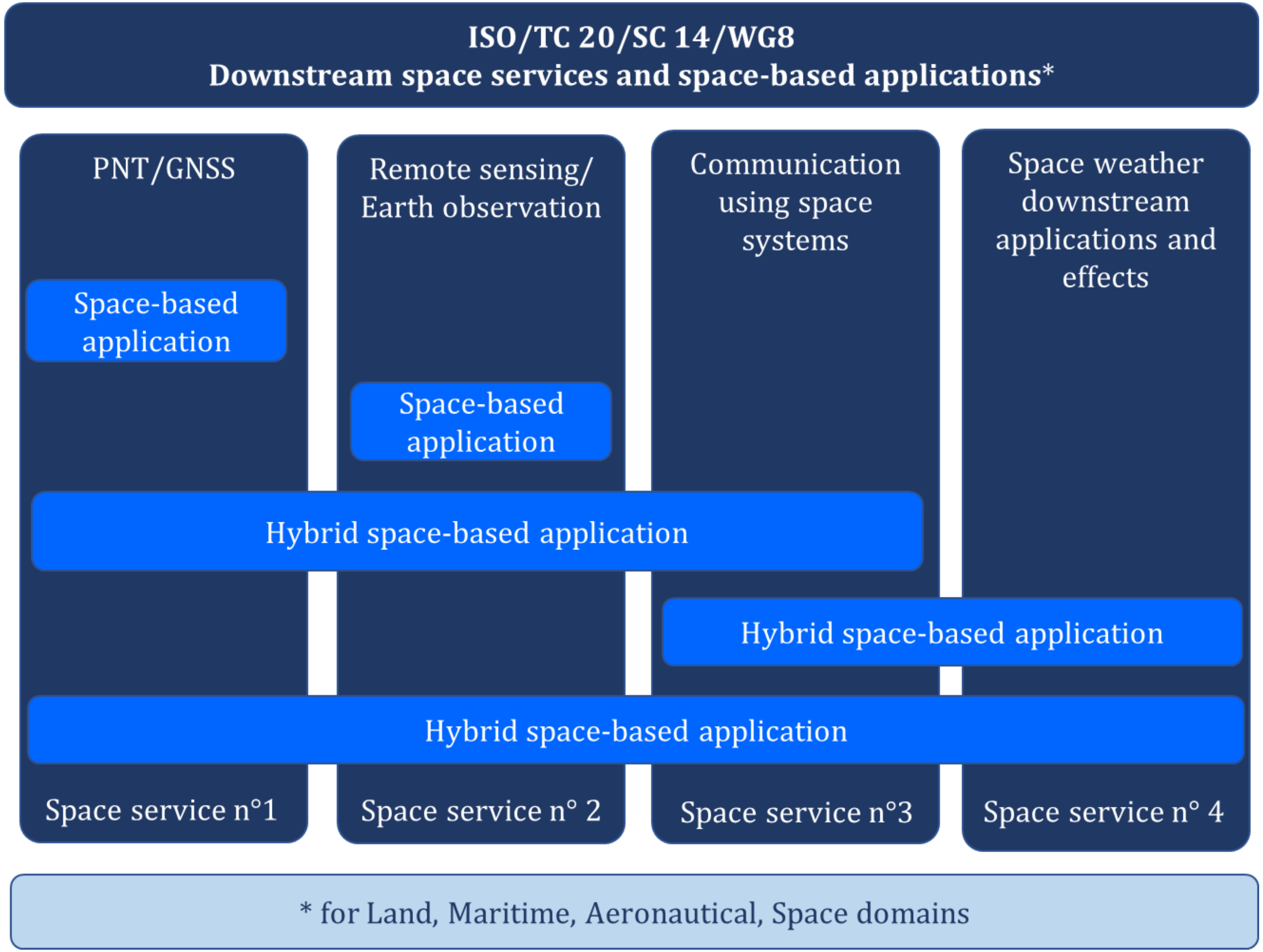
Space service --- service using space segment as part of system
Space-based application --- application using space service
Downstream space service --- space service to direct to terrestrial surface from space for end users
Downstream space-based application --- space-based application using downstream space service

WG8「宇宙利用サービス」

Downstream space services and space-based applications



「宇宙利用サービス」４つの柱



① 衛星測位

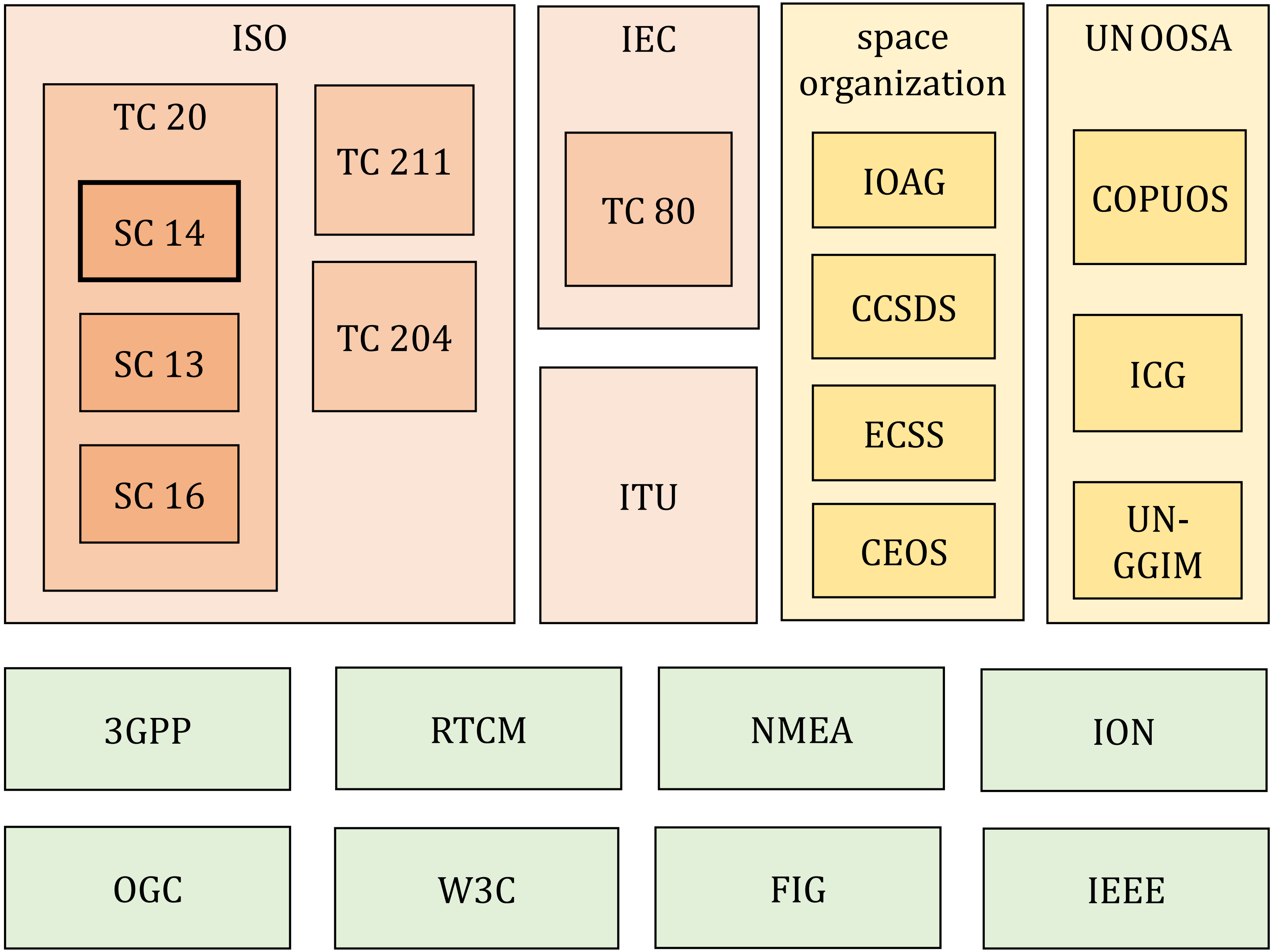
② 地球観測

③ 衛星通信

④ 宇宙天気

[略語]
PNT:
Positioning, Navigation, and Timing
測位：
位置計測・航法・調時

TC 20/SC 14/WG8「宇宙利用サービス」関連組織



開発が進む「宇宙利用サービス」に関する国際規格の体系

衛星測位　リモセン　衛星通信　宇宙天気

6カ国+α　航法衛星

衛星管制局

6カ国+α

ISO 24246
測位補強センター
（発行済）

約600カ所

ユーザ機器

ISO 24245 GNSS受信機分類コード
（発行済）

ISO/TS 22591 安全要求のある高精度測位サービス（発行済）

ISO/CD 13657 位置情報交換フォーマット（委員会原案審議中）

：
：

30–70億台

ISO/CD 16215-1 衛星測位(PNT)サービス-アーキテクチャーの基礎
（委員会原案審議中）

ISO 18197 センチメータ級測位の宇宙利用サービス要件（発行済）

ISO 20930
マイクロ波受動センサの校正要求
（発行済）

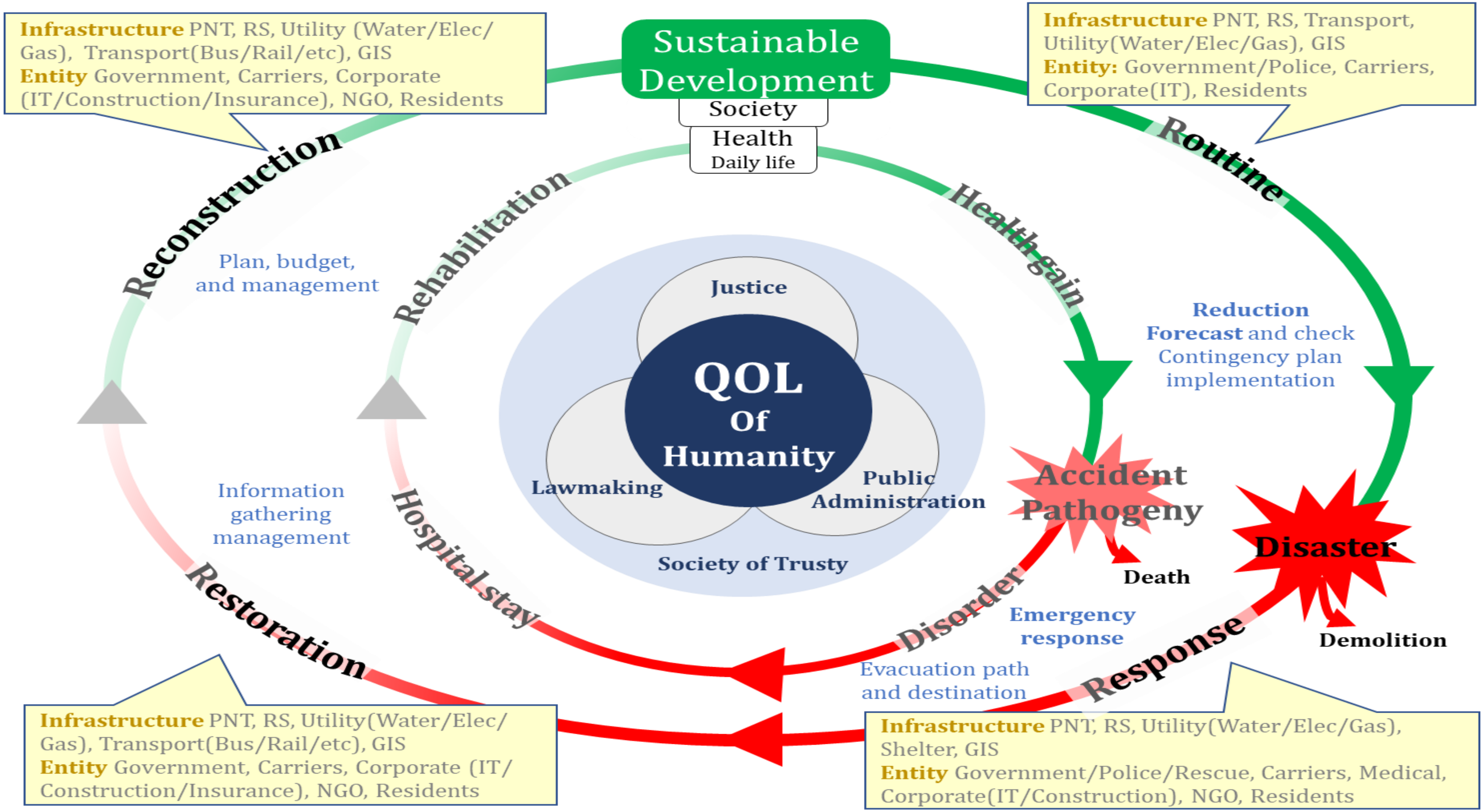
ISO/AWI 22550
光学地球観測のポインティング管理
（作業原案審議中）

宇宙天気の民生用サービス
（国際討議開始）

低軌道衛星による通信応用サービス
（国際討議準備中）

IEC 61108-8
海洋航行と無線通信機器
みちびき測位受信機
（委員会原案作成中）

WG8 トップレベル文書Annex から抜粋
Space systems for the Quality of Life



月の時系について

月の時系

月の時系の標準化

2024年4月にホワイトハウスがNASAに対して月の時系に関する指示：
・2024年末迄に月標準時を検討
・2026年末迄に月の時刻の標準化を実装するための戦略提出を要求

LTC(Coordinated Lunar Time)を策定
地球のUTCに対応

月標準時の条件として，協定世界時へのトレーサビリティを要求

EXECUTIVE OFFICE OF THE PRESIDENT
OFFICE OF SCIENCE AND TECHNOLOGY POLICY
WASHINGTON, D.C. 20502

April 2, 2024

MEMORANDUM FOR DEPARTMENTS AND AGENCIES PARTICIPATING IN THE WHITE HOUSE CISLUNAR TECHNOLGY STRATEGY INTERAGENCY WORKING GROUP

FROM: Arati Prabhakar, Assistant to the President for Science and Technology and Director, Office of Science and Technology Policy

SUBJECT: Policy on Celestial Time Standardization in Support of the National Cislunar Science and Technology (S&T) Strategy

This memorandum outlines the Biden-Harris Administration's policy to establish time standards at and around celestial bodies other than Earth to advance the National Cislunar S&T Strategy.[1] OSTP directs federal departments and agencies to align their planning and policies with this memorandum.

The approach to establish time standards consists of the definition, development, and implementation of a distinct reference time at each celestial body and its surrounding space environment. Each new time standard developed will include the following features:

1. *Traceability* to Coordinated Universal Time (UTC);[2]
2. *Accuracy* sufficient to support precision navigation and science;
3. *Resilience* to loss of contact with Earth; and
4. *Scalability* to space environments beyond the Earth-Moon system

Federal agencies will develop celestial time standardization with an initial focus on the lunar surface and missions operating in Cislunar space, with sufficient traceability to support missions to other celestial bodies.

月の時間の規定(1)

Concluding remarks

Terms corresponding to the potentials of the Earth and Moon and definitions of the geoid and selenoid:	$-\frac{GM_e}{Dc^2}-\frac{\phi_0}{c^2}, \quad -\frac{GM_m}{Dc^2}-\frac{\phi_{0m}}{c^2}$
Terms corresponding to the speeds of the Earth and Moon w.r.t. the Earth-Moon center of mass frame:	$-\frac{V_e^2}{2c^2}+\frac{V_m^2}{2c^2}$
If the appropriate terms are not accounted correctly, results in incorret estimates of rate offsets:	$\sim 58.7\ \mu s, \sim 57.0\ \mu s, \sim 56.5\ \mu s$
Tidal corrections are of the order of :	~ less than 10 ns.
Corrections due to Lorentz contraction:	~ less than 10 ps.

月の時間は地球より
１日57μs早く進む
（重力が小さいため）

参考文献：Bijunath R. Patra and Neil Ashby, Clocks on the Moon and in CIS-lunar space: lessons from GPS, 64th CGSIC, Baltimore, September, 2024

月の時間の規定(2)

Concluding remarks

A freely falling coordinate system may be used to accurately estimate the Moon's rate offsets from the Earth’s geoid.

Using the above, establishing a coordinate time for the Moon is very similar to establishing a coordinate time (also known as GPS time) for the Earth.

This framework can be extended to compute rate offsets of other celestial bodies in the solar system and Lagrange points (cislunar space).

Efforts to establish a reference frame and a reference time are continuing.

月の時系は、地球の時系と
同様に規定できる。
これは他の天体やラグランジュ点
にも応用できる。
月の時系と基準座標系を規定する
努力を続ける。

参考文献： Bijunath R. Patra and Neil Ashby, Clocks on the Moon and in CIS-lunar space: lessons from GPS, 64th CGSIC, Baltimore, September, 2024

月の基準座標系について

LunaNet 標準 NASA/ESA/JAXA

Explore　Search...　NASA　News & Events　Multimedia　NASA+ LIVE

3 MIN READ

LunaNet Interoperability Specification

Catherine G. Manning

FEB 08, 2023

ARTICLE

CONTENTS

The purpose of the LunaNet Interoperability Specification (LNIS) is to define a framework of mutually agreed-upon standards to be applied by users and service providers in a cooperative network supporting missions on and around the Moon. The framework would apply to communication transmission services for science, exploration and commercial operations, distribution of navigation and timing references, and sharing of information such as space weather alerts. These standards can be introduced as part of upcoming missions to and around the Moon and can accommodate expansion as new commercial and government users and service providers join in an open and evolving architecture. The standards are intended to be compatible with other space communications standards established to date, but are focused on lunar operations, and in particular future lunar communications relay and navigation capabilities.

The development of the LunaNet Interoperability Specification has been a collaboration between NASA and the European Space Agency (ESA). As the specification is refined and new versions are produced, the effort will continue to seek input from the broad community of potential commercial service providers, lunar mission users, and other space agencies.

LunaNet 標準 NASA/ESA/JAXA

Version 4 (current version)

Draft Version 5 (for review)

Version 4 (current version)

The LunaNet Interoperability Specification – Version 4 was published online on September 12, 2022 and can be found at the link below.

LunaNet Interoperabilty Specification – Version 4

Draft Version 5 (for review)

A proposed update to the LNIS has been produced and is available at the link below. There will be a period for review and feedback from the international industry and government community before a new LNIS Version 5 is finalized.

Any commercial and government entities that wish to submit comments, questions, or suggestions may do so using the form provided below. **We request that these inputs be submitted before the end of November 2023**.

NASA and ESA will also be conducting reviews with potential mission users and other internal organizations, service providers, the Interagency Operations Advisory Group (IOAG), and the Consultative Committee for Space Data Systems (CCSDS).

LNIS Draft Version 5, and a draft applicable document (AD1) can be found at the links below:

- LunaNet Interoperability Specification Draft Version 5
- LunaNet Signal-In-Space Recommended Standard – Augmented Forward Signal (AD1)

Those wishing to submit questions, comments, or suggestions can do so using the spreadsheet template below and sending it as an attachment via **email**.

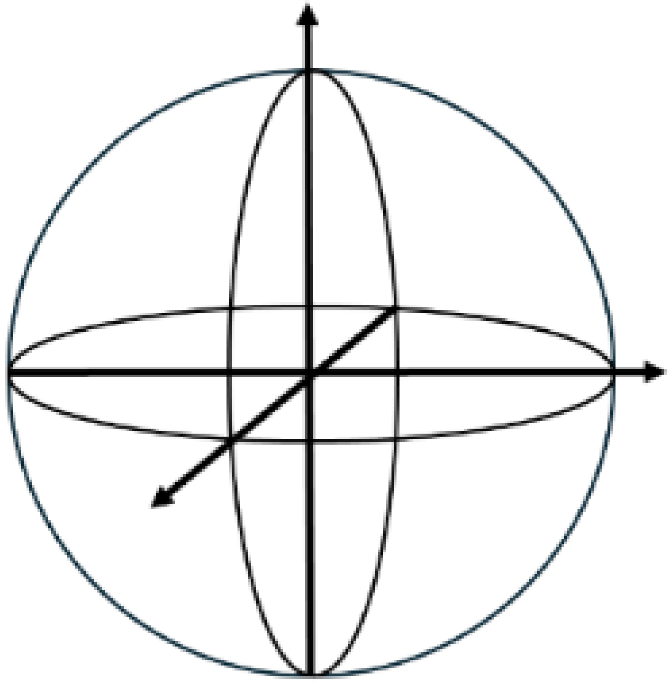
LNIS Review Draft Version 5 Comment Form

Please submit all inputs no later than November 30, 2023.

Space Communications and Navigation Program (SCaN)

座標系の規定

定義：Definition



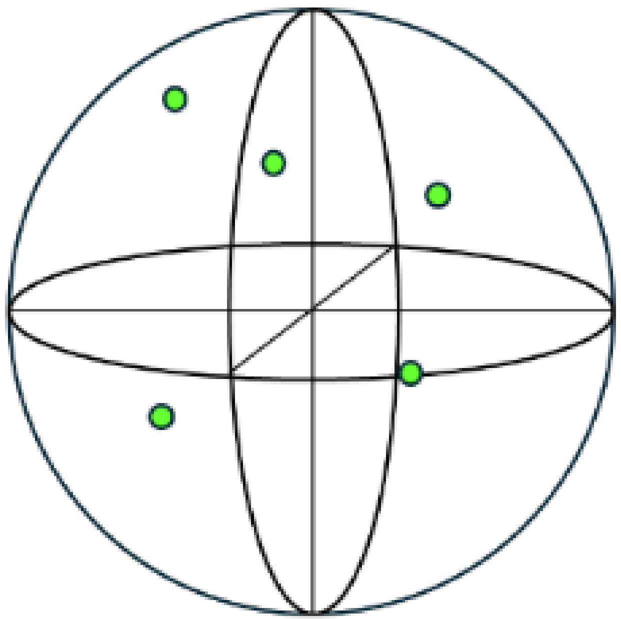
Origin
原点

Axis
座標軸

Scale
目盛

Time valiance
時間変動

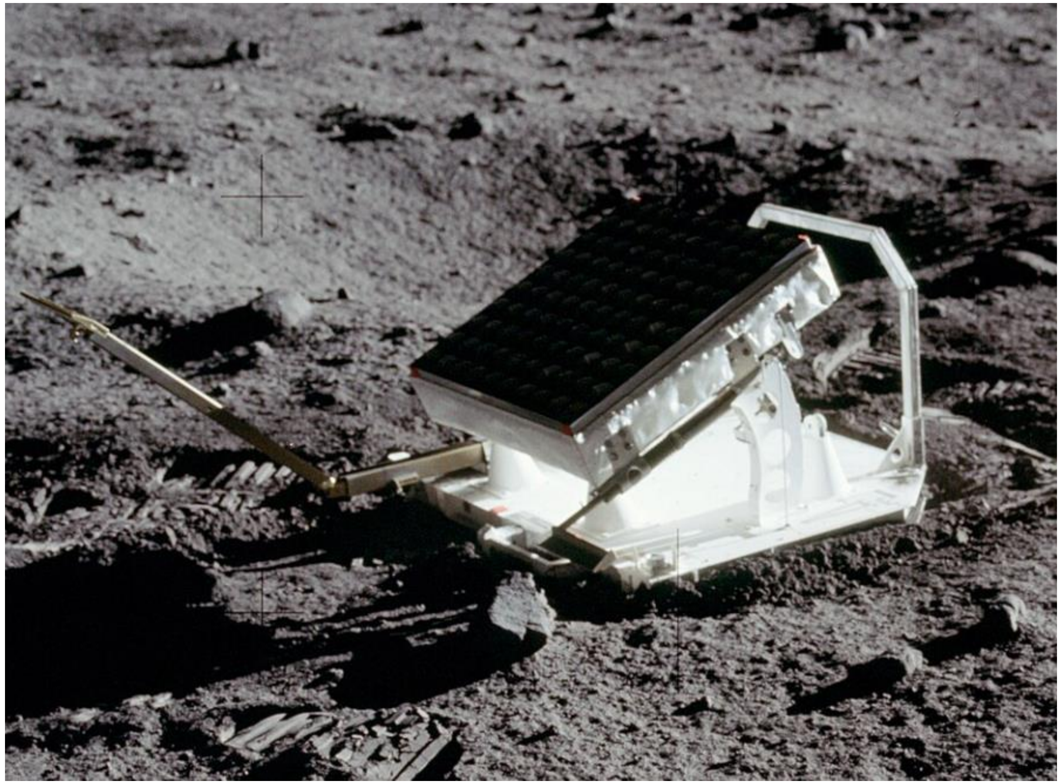
実現：Realization



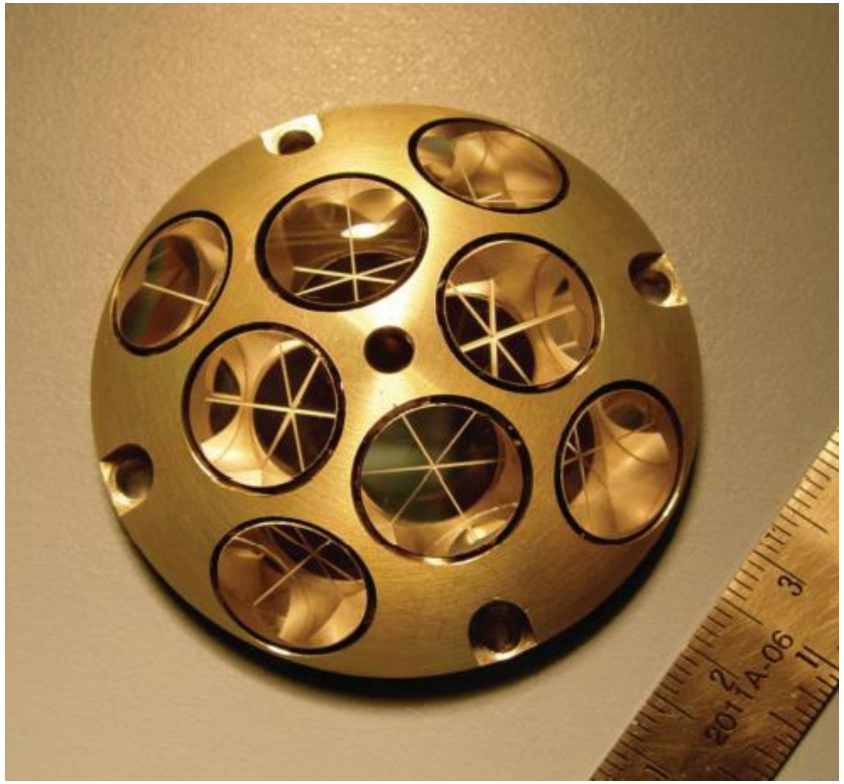
Reference Points
基準点

Coordinates Values
座標値リスト

レーザー・リトロ・リフレクター



アポロ11号のリトロリフレクター



NASA標準のリトロリフレクター

座標値リスト

Retroreflectors	DE440 PA Frame (m) （PA系）	DE421 MER Frame (m) （ME系）
Apollo 11	1591967.049	1591747.649
	690698.573	691222.200
	21004.461	20398.110
Apollo 14	1652689.369	1652818.682
	−520998.431	−520454.587
	−109729.869	−110361.165
Apollo 15	1554678.104	1554937.504
	98094.498	98604.886
	765005.863	764412.810
Lunokhod 2	1339363.598	1339388.213
	801870.995	802310.527
	756359.260	755849.393
Lunokhod 1	1114291.452	1114958.865
	−781299.273	−780934.127
	1076059.049	1075632.692

月の基準座標系について

- ME（Moon/Earth polar axis）系
  よく使われている。
- PA（Principal Axis）系

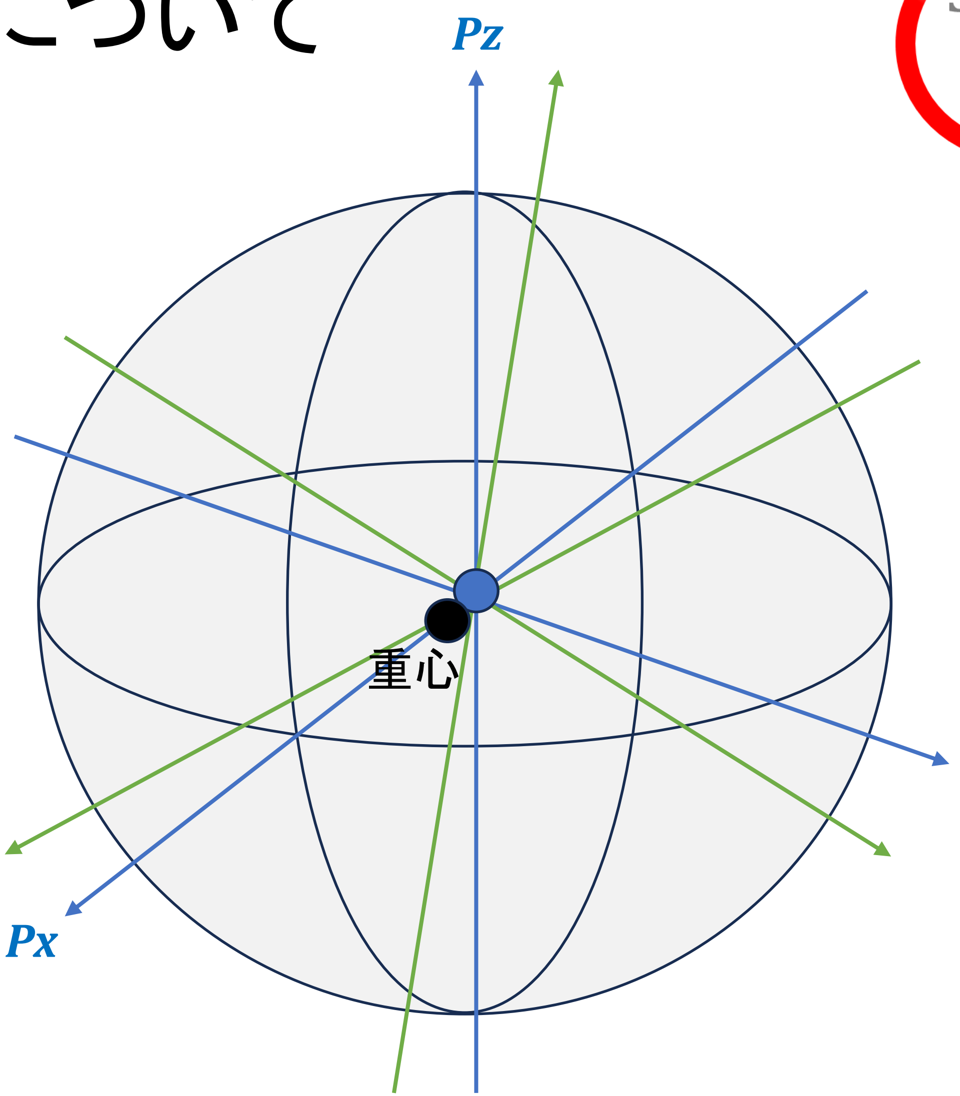
任意軸周りの慣性モーメント（テンソル）

$$J_o = \begin{bmatrix} J_x & -J_{xy} & -J_{xz} \\ -J_{xy} & J_y & -J_{yz} \\ -J_{xz} & -J_{yz} & J_z \end{bmatrix}$$

慣性主軸周りの慣性モーメント（テンソル）

$$J_{PA} = \begin{bmatrix} J_{Px} & 0 & 0 \\ 0 & J_{Py} & 0 \\ 0 & 0 & J_{Pz} \end{bmatrix}$$

NASA JPL(2020) 論文で優位性を説明



自転軸：慣性モーメントの最大軸
経度ゼロ：慣性モーメントが最小値（地球方向）

慣性モーメント最小主軸が地球を向く理由

月と地球の相互作用によって発生する潮汐ポテンシャルエネルギー U は、月の自転と地球の相対位置に依存する．このエネルギーはルジャンドル多項式を用いて式(6)のように表すことができる．

$$U = -\frac{GM_eM_mR_m^2}{r^3}\left\{\frac{1}{2}(3\cos^2\theta - 1)\right\} \tag{6}$$

ここで，各項は以下のように定義される．

G： 万有引力定数

M_e： 地球の質量

M_m： 月の質量

R_m： 月の半径

r： 月と地球の距離

θ： 最小慣性モーメント主軸と地球方向との角度

月がエネルギーを最小化するには、ポテンシャルエネルギー U を最小化する必要がある．エネルギーを θ で式(7)のように微分して、その極小点を求める．

$$\frac{\partial U}{\partial \theta} = \frac{GM_eM_mR_m^2}{r^3} 3\cos\theta\sin\theta \tag{7}$$

この式が 0 になる条件は次のとおりである．

$$3\cos\theta\sin\theta = 0 \tag{8}$$

$$\sin 2\theta = 0 \tag{9}$$

この方程式の解は，

$$\theta = 0 \text{ または } \theta = \pi$$

となる．

$\theta = 0$ の場合，最小慣性モーメント主軸は地球を向く．

参考文献: 浅里、村田、岡村、「月の基準座標系と時系の国際規定に関する研究」, 3M05, 宇宙科学連合講演会 2024

国連GNSS国際委員会(ICG-18)にて調整

- ◆ 基準座標系を設定するには基準点が少なすぎる。今後は増えていく。
- ◆ International Standard ではなく、Technical Specification (TS) にする。
- ◆ ME系とPA系を併記せざるをえない。