LUNAR PNT USER/TEST EQUIPMENT & TECHNOLOGY

PRODUCTS FROM DESIGN TO OPERATIONS

Needs and Objectives	Architecture and Concept of Operations	Requirements Development	Preliminary Design	Detailed Design	Ground Testing	Flight Verification	Validation

Service Definition

Operational Concept

Interface Control Document

In-situ Performance

Operational Interface

System Health and Status
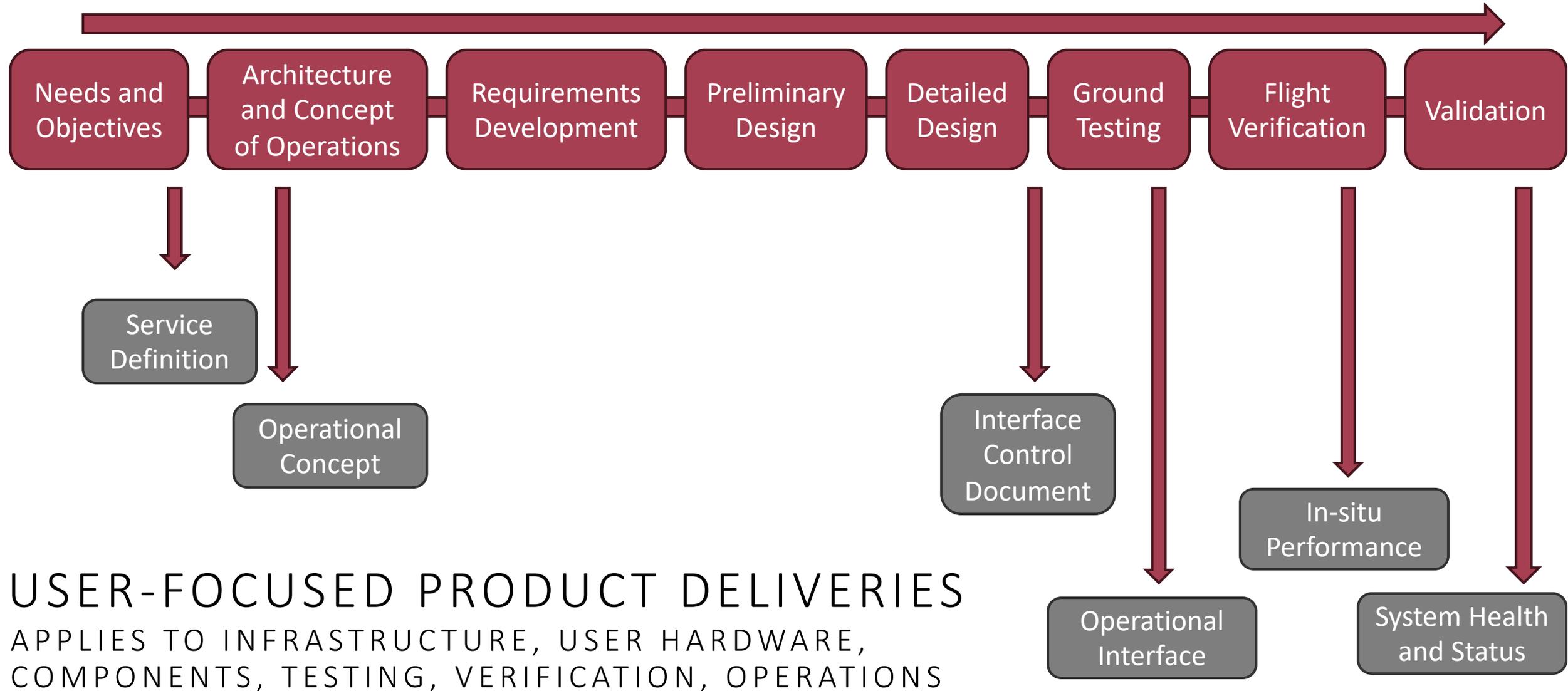
USER-FOCUSED PRODUCT DELIVERIES
APPLIES TO INFRASTRUCTURE, USER HARDWARE, COMPONENTS, TESTING, VERIFICATION, OPERATIONS

COMMON USER QUESTIONS AND NEEDS

At Mission Concept:

What can the system provide and when?

How do I interface with it?

What is the maturity of the system?

At Preliminary Design:

Does hardware to use it exist or do I build my own?

What is performance of system? How do I balance with other onboard systems?

At Detailed Design:

What is operational interface?

What is interface to receiver?

How do I process the received data?

At Verification:

What data can I use to verify my system operates correctly with the deployed signals?

How do I perform ground testing to verify end to end capability?

Prior to Flight:

How do I know the system is working?

How do I schedule services?

In flight:

How do I check out the services?

How do I monitor health and status?

REFLECTION ON 2025 WORKSHOP

Takeaways from 2025 Presentations:

- Key User Equipment is in Active Development

- User Support Equipment Being Developed

- Underlying Techniques are Being Tested and Demonstrated

- Long-term Capabilities and Needs are Being Considered Now

- Demonstration Missions and Validation of Early Constellations in Work

Future Recommendations:

- Consider Annual "State of the Art" to Track User Equipment

- Usage and Implementation of Key Foundations being Developed by International Standards Community

- Ensure Protection of Existing Spectrum to Interference and Validate Compatibility through Ground-based Testing

- Develop Common Formats for User Interfaces

TOPICS COVER MANY USER PERSPECTIVES

Lunar PNT User/Test Equipment & Technology – part 1:

"Flight Experience and Results of the Lunar GNSS Receiver Experiment (LuGRE)", Joel Parker (NASA)

"Lunar Data Network PNT Systems Capability and Interfaces Status", Jason Leonard (Intuitive Machines)

"Towards a Sustainable Lunar Ecosystem: Bridging Technical Developments to Policy Priorities in Lunar PNT", Toshihiro Shibukawa (ArkEdge Space)

"Lunar S-band Pseudolite System Architecture & User Equipment", Ashish Shukla (ISRO)

"Enabling Future Lunar Operations through PNT: A GMV User Perspective", Danilo Forte (GMV)

"PNT Moon Surface Station: Performance Analysis and First Demonstrations", Luca Canzian (Qascom)

"Inter-satellite-link-aided Collaborative Navigation and Time Transfer of a Lunar PNT Constellation", Pradipto Ghosh (JHU APL)

"Integrity monitoring strategies for LCNS users", Heiko Engwerda (NLR)

"A simulator to compute interference from lunar surface wireless to lunar PNT; architecture and results", Jean-Luc Issler (CNES) (virtual)

"End-to-End Simulation Framework for LunaNet and Mars GPS-Like Signals for Software Receiver Assessment", Ricardo Verdeguer Moreno (Spirent)

Lunar PNT User/Test Equipment & Technology – part 2:

"GNSS Weak Signal-based Orbit Determination Practice and Cislunar Space Application Analysis", Biao Jin (Space Star Technology Co., Ltd.)

"CesiumAstro 2026: Missions & Technologies", Dylan Pfeifer (Cesium)

"An optical clock on the Moon? Some key figures", Fabien Droz (Rolex Quantum)

"Miniature clocks for cislunar and lunar application - Upcoming Technologies and Roadmap", Grégory Moura (Safran)

What can the system do? How to validate performance?

Lunar PNT User/Test Equipment & Technology – part 1:

"Flight Experience and Results of the Lunar GNSS Receiver Experiment (LuGRE)", Joel Parker (NASA)

"Lunar Data Network PNT Systems Capability and Interfaces Status", Jason Leonard (Intuitive Machines)

"Towards a Sustainable Lunar Ecosystem: Bridging Technical Developments to Policy Priorities in Lunar PNT", Toshihiro Shibukawa (ArkEdge Space)

"Lunar S-band Pseudolite System Architecture & User Equipment", Ashish Shukla (ISRO)

"Enabling Future Lunar Operations through PNT: A GMV User Perspective", Danilo Forte (GMV)

"PNT Moon Surface Station: Performance Analysis and First Demonstrations", Luca Canzian (Qascom)

"Inter-satellite-link-aided Collaborative Navigation and Time Transfer of a Lunar PNT Constellation", Pradipto Ghosh (JHU APL)

"Integrity monitoring strategies for LCNS users", Heiko Engwerda (NLR)

"A simulator to compute interference from lunar surface wireless to lunar PNT; architecture and results", Jean-Luc Issler (CNES) (virtual)

"End-to-End Simulation Framework for LunaNet and Mars GPS-Like Signals for Software Receiver Assessment", Ricardo Verdeguer Moreno (Spirent)

Lunar PNT User/Test Equipment & Technology – part 2:

"GNSS Weak Signal-based Orbit Determination Practice and Cislunar Space Application Analysis", Biao Jin (Space Star Technology Co., Ltd.)

"CesiumAstro 2026: Missions & Technologies", Dylan Pfeifer (Cesium)

"An optical clock on the Moon? Some key figures", Fabien Droz (Rolex Quantum)

"Miniature clocks for cislunar and lunar application - Upcoming Technologies and Roadmap", Grégory Moura (Safran)

What hardware exists? Do I build something myself?

Lunar PNT User/Test Equipment & Technology – part 1:

"Flight Experience and Results of the Lunar GNSS Receiver Experiment (LuGRE)", Joel Parker (NASA)

"Lunar Data Network PNT Systems Capability and Interfaces Status", Jason Leonard (Intuitive Machines)

"Towards a Sustainable Lunar Ecosystem: Bridging Technical Developments to Policy Priorities in Lunar PNT", Toshihiro Shibukawa (ArkEdge Space)

"Lunar S-band Pseudolite System Architecture & User Equipment", Ashish Shukla (ISRO)

"Enabling Future Lunar Operations through PNT: A GMV User Perspective", Danilo Forte (GMV)

"PNT Moon Surface Station: Performance Analysis and First Demonstrations", Luca Canzian (Qascom)

"Inter-satellite-link-aided Collaborative Navigation and Time Transfer of a Lunar PNT Constellation", Pradipto Ghosh (JHU APL)

"Integrity monitoring strategies for LCNS users", Heiko Engwerda (NLR)

"A simulator to compute interference from lunar surface wireless to lunar PNT; architecture and results", Jean-Luc Issler (CNES) (virtual)

"End-to-End Simulation Framework for LunaNet and Mars GPS-Like Signals for Software Receiver Assessment", Ricardo Verdeguer Moreno (Spirent)

Lunar PNT User/Test Equipment & Technology – part 2:

"GNSS Weak Signal-based Orbit Determination Practice and Cislunar Space Application Analysis", Biao Jin (Space Star Technology Co., Ltd.)

"CesiumAstro 2026: Missions & Technologies", Dylan Pfeifer (Cesium)

"An optical clock on the Moon? Some key figures", Fabien Droz (Rolex Quantum)

"Miniature clocks for cislunar and lunar application - Upcoming Technologies and Roadmap", Grégory Moura (Safran)

How do I use and monitor it?

Lunar PNT User/Test Equipment & Technology – part 1:

"Flight Experience and Results of the Lunar GNSS Receiver Experiment (LuGRE)", Joel Parker (NASA)

"Lunar Data Network PNT Systems Capability and Interfaces Status", Jason Leonard (Intuitive Machines)

"Towards a Sustainable Lunar Ecosystem: Bridging Technical Developments to Policy Priorities in Lunar PNT", Toshihiro Shibukawa (ArkEdge Space)

"Lunar S-band Pseudolite System Architecture & User Equipment", Ashish Shukla (ISRO)

"Enabling Future Lunar Operations through PNT: A GMV User Perspective", Danilo Forte (GMV)

"PNT Moon Surface Station: Performance Analysis and First Demonstrations", Luca Canzian (Qascom)

"Inter-satellite-link-aided Collaborative Navigation and Time Transfer of a Lunar PNT Constellation", Pradipto Ghosh (JHU APL)

"Integrity monitoring strategies for LCNS users", Heiko Engwerda (NLR)

"A simulator to compute interference from lunar surface wireless to lunar PNT; architecture and results", Jean-Luc Issler (CNES) (virtual)

"End-to-End Simulation Framework for LunaNet and Mars GPS-Like Signals for Software Receiver Assessment", Ricardo Verdeguer Moreno (Spirent)

Lunar PNT User/Test Equipment & Technology – part 2:

"GNSS Weak Signal-based Orbit Determination Practice and Cislunar Space Application Analysis", Biao Jin (Space Star Technology Co., Ltd.)

"CesiumAstro 2026: Missions & Technologies", Dylan Pfeifer (Cesium)

"An optical clock on the Moon? Some key figures", Fabien Droz (Rolex Quantum)

"Miniature clocks for cislunar and lunar application - Upcoming Technologies and Roadmap", Grégory Moura (Safran)

What are the supporting hardware elements I need?

Lunar PNT User/Test Equipment & Technology – part 1:

"Flight Experience and Results of the Lunar GNSS Receiver Experiment (LuGRE)", Joel Parker (NASA)

"Lunar Data Network PNT Systems Capability and Interfaces Status", Jason Leonard (Intuitive Machines)

"Towards a Sustainable Lunar Ecosystem: Bridging Technical Developments to Policy Priorities in Lunar PNT", Toshihiro Shibukawa (ArkEdge Space)

"Lunar S-band Pseudolite System Architecture & User Equipment", Ashish Shukla (ISRO)

"Enabling Future Lunar Operations through PNT: A GMV User Perspective", Danilo Forte (GMV)

"PNT Moon Surface Station: Performance Analysis and First Demonstrations", Luca Canzian (Qascom)

"Inter-satellite-link-aided Collaborative Navigation and Time Transfer of a Lunar PNT Constellation", Pradipto Ghosh (JHU APL)

"Integrity monitoring strategies for LCNS users", Heiko Engwerda (NLR)

"A simulator to compute interference from lunar surface wireless to lunar PNT; architecture and results", Jean-Luc Issler (CNES) (virtual)

"End-to-End Simulation Framework for LunaNet and Mars GPS-Like Signals for Software Receiver Assessment", Ricardo Verdeguer Moreno (Spirent)

Lunar PNT User/Test Equipment & Technology – part 2:

"GNSS Weak Signal-based Orbit Determination Practice and Cislunar Space Application Analysis", Biao Jin (Space Star Technology Co., Ltd.)

"CesiumAstro 2026: Missions & Technologies", Dylan Pfeifer (Cesium)

"An optical clock on the Moon? Some key figures", Fabien Droz (Rolex Quantum)

"Miniature clocks for cislunar and lunar application - Upcoming Technologies and Roadmap", Grégory Moura (Safran)

SUMMARY OF 2026 PRESENTATIONS

- ***Consider Annual "State of the Art" to Track User Equipment?***
  - Presentations covered updates from multiple vendors developing flight hardware and simulation support

- ***Usage and Implementation of Key Foundations being Developed by International Standards Community***
  - Products in development by standards bodies, working towards International approval
  - Beginning to show up in vendor designs; Waiting for formal delivery of Service Catalogs and ICDs to verify

- ***Ensure Protection of Existing Spectrum to Interference and Validate Compatibility through Ground-based Testing***
  - Current receiver development is supported by limited ground testing; plans towards compatibility testing vary by service provider and still in work

- ***Develop Common Formats for User Interfaces***
  - Other sessions covered formats being developed (Lunar RINEX), but still work to go for equipment interfaces

REMAINING QUESTIONS FOR FUTURE DISCUSSION

Testing and Validation:

How do I verify the simulators against flight data?

What are flight opportunities planned to gather real flight data and validate capability?

How to approach in-flight monitoring and health and status external to a constellation?

What organizations would provide monitor and recovery data? What is analog to autonomous monitoring stations?

What is vendor's approach to ground compatibility and pre-flight checks?

Navigation System Development:

What is timeline for hardware components to support Lunar PNT?

How to approach common output interface of receiver? (custom interfaces vs CCSDS vs NMEA-like?)

How to approach data exchange and monitoring? Implementation path to Lunar RINEX?

What is best approach to implement Lunar timing models and transfers?

How to approach coordination and use of multiple constellations with different performance requirements?

FOR CLOSING SESSION

USER EQUIPMENT AND TECHNOLOGIES SUMMARY

- Continued development by commercial and agency partners in development of user equipment both for ground testing and flight hardware

- Need to certify flight systems will increase, more focus on ground verification and validation

- 2026 has several high-profile Lunar missions planned, expect to continue to gain insight into user experiences and challenges

- As international standards become adopted, need to ensure user equipment and test capability also implement these

- Components of user equipment coming together, but integrated solution still tightly integrated with unique user designs

- Focus so far has been on validation of services and demonstration of systems, over next year expect to start seeing more mature surface users