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National Aeronautics and Space Administration

Communications for UAS Integration in the NAS Phase 2: Satellite Communications and Terrestrial Extension

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Introduction

Integration of Unmanned Aircraft Systems (UAS) into the National Airspace System (NAS) – controlled (non-segregated) airspace

- Command and Control (C2) communications link
  - Line of Sight (LOS) terrestrial link
  - Beyond (radio) Line-of-Sight (BLOS) satellite link
- Performance standards must be developed and validated.

NASA's UAS Integration in the NAS

- 2012-2016: Phase 1 focused on radio line-of-sight (LOS) C2 links
- 2017-2020: Phase 2 will focus on beyond radio line-of-sight (BLOS) C2 links.

Uplink (GCS to RPAS)

Activity	bps
Telecommand	4593
Navigational Aid Setting	666
ATC Voice	4800
ATC Data	49
Total	**10108**

Downlink (RPAS to GCS)

Activity	bps
Telemetry	7975
Navaid Display Data	1137
ATC Voice	4800
ATS Data	59
DAA	4800
Weather	27770
Video	270000
Total	**316161**

UAS in the NAS C2 Subproject Objectives

Frequency spectrum allocations for both LOS and BLOS UAS C2

- Analysis, sharing studies, and advocacy to support the establishment of spectrum allocations technical requirements of operational spectrum use Beyond

Develop/validate UAS C2 Minimum Operational Performance Standards (MOPS)

- Technology assessment, collaborative prototype development, laboratory and flight testing

Develop security recommendations for civil UAS C2

- Establish security requirements, develop, test and validate technical recommendations

Support recommendations for integration of UAS in the NAS

- Through flight testing, C2 system modeling and simulation, and analysis develop and validate technical recommendations for integration of UAS into the airspace

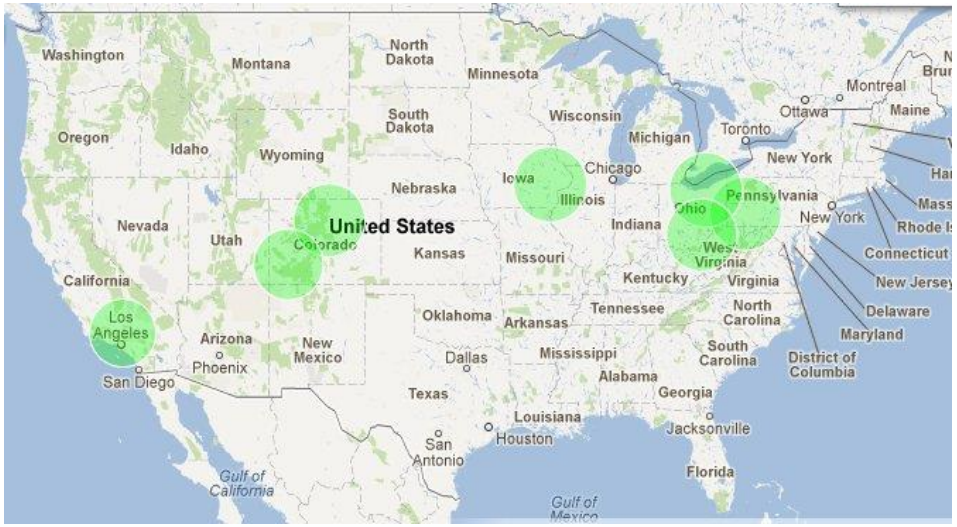
C2 Subproject Phase 1 Overview

Air-Ground Channel Propagation

Lockheed Orion S-3B research aircraft. Inset: antenna locations

Air-ground channel characterization in 7 different locations studied several terrain types:

- Mountainous
- Hilly
- Flat terrain
- Near-urban
- Suburban
- Salt water
- Fresh water

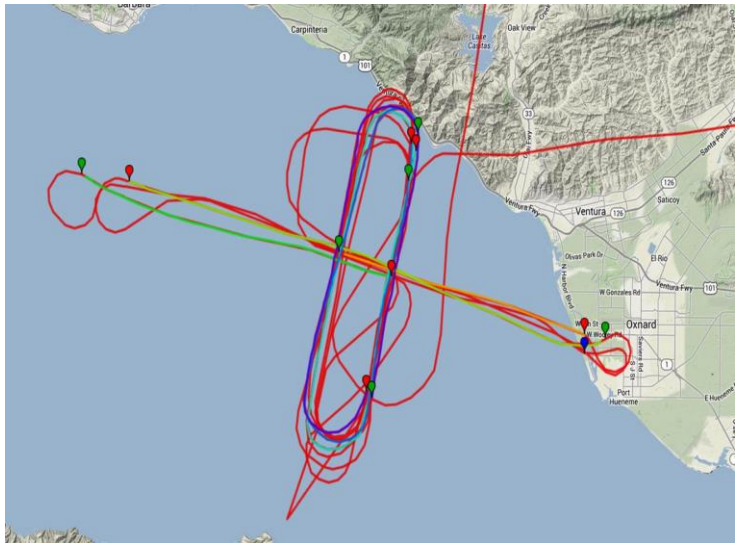


AG channel measurement flight test locations

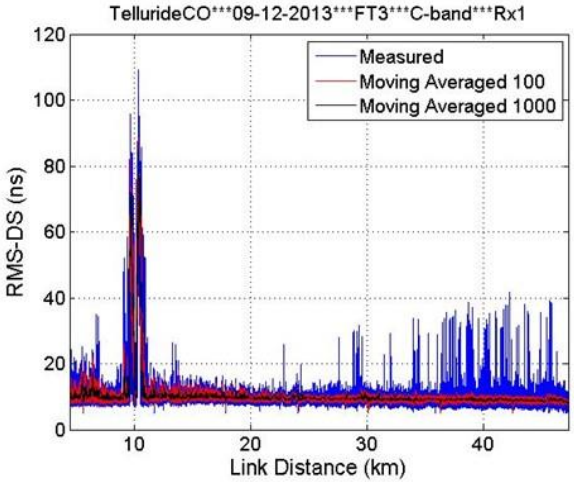
C2 Subproject Phase 1 Overview

Air-Ground Channel Propagation

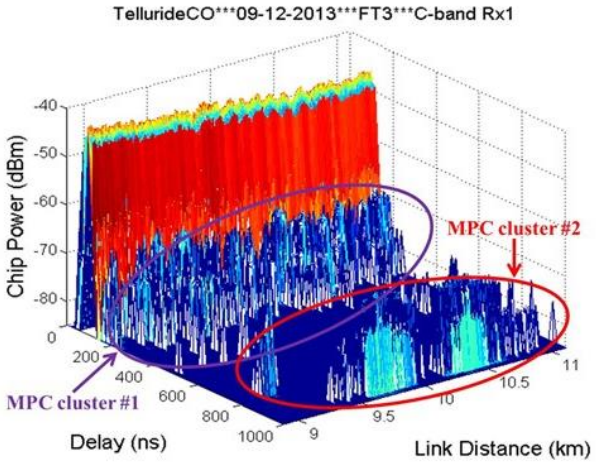
- Flight tracks provided varied orientations relative to the ground station and terrain.
- Channel impulse responses were measured and power delay profiles calculated.
- Channel models were developed for all terrain types.



Example Flight Tracks for Over Sea Propagation Measurements near Oxnard, California



RMS-Delay Spread vs. Link Distance

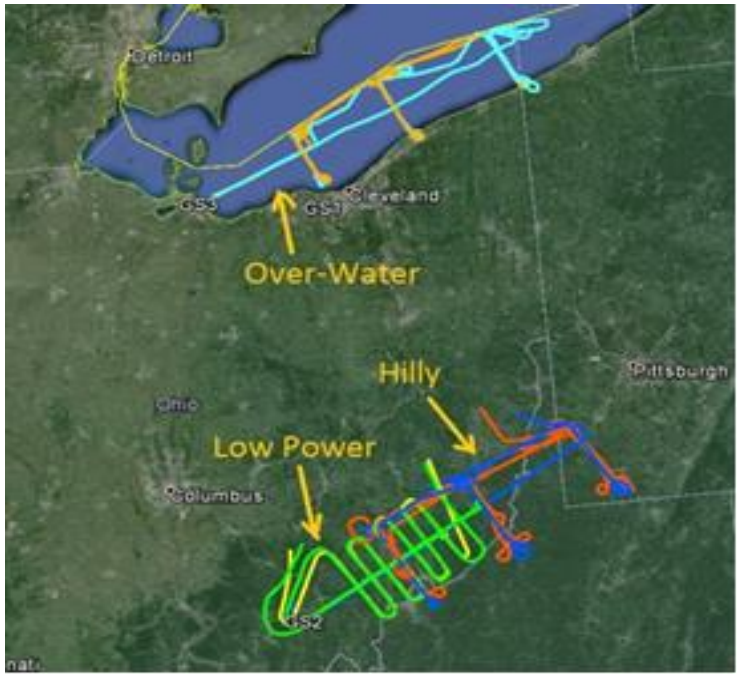


Power Delay Profiles

C2 Subproject Phase 1 Overview

C2 Radio Development and Testing

- Shared-resource cooperative agreement with Rockwell Collins
- Five generations of prototype C2 radios, both ground and airborne versions, were used to validate the MOPS
- Radios operated in the 960 – 977 MHz and 5030 – 5091 MHz bands.
- A complete CNPC system
  - Interface to a ground based pilot station
  - Transmission of CNPC data to/from more than one ground station
  - Onboard reception and transmission of CNPC data on more than one UA
- Testing included
  - Hand-off, coverage limits
  - Signal loss and recovery
  - Mountainous, desert, hilly, urban, and over water environments
- C2 Flight Testing Statistics (2012-2016)
  - >65 mission flights flown at 12 locations
  - >200 hours of flight data collection
  - >12,000 miles traveled by portable GS



C2 Radio Flight Test Tracks for Several Flights in Northern and Southern Ohio

C2 Subproject Phase 1 Overview

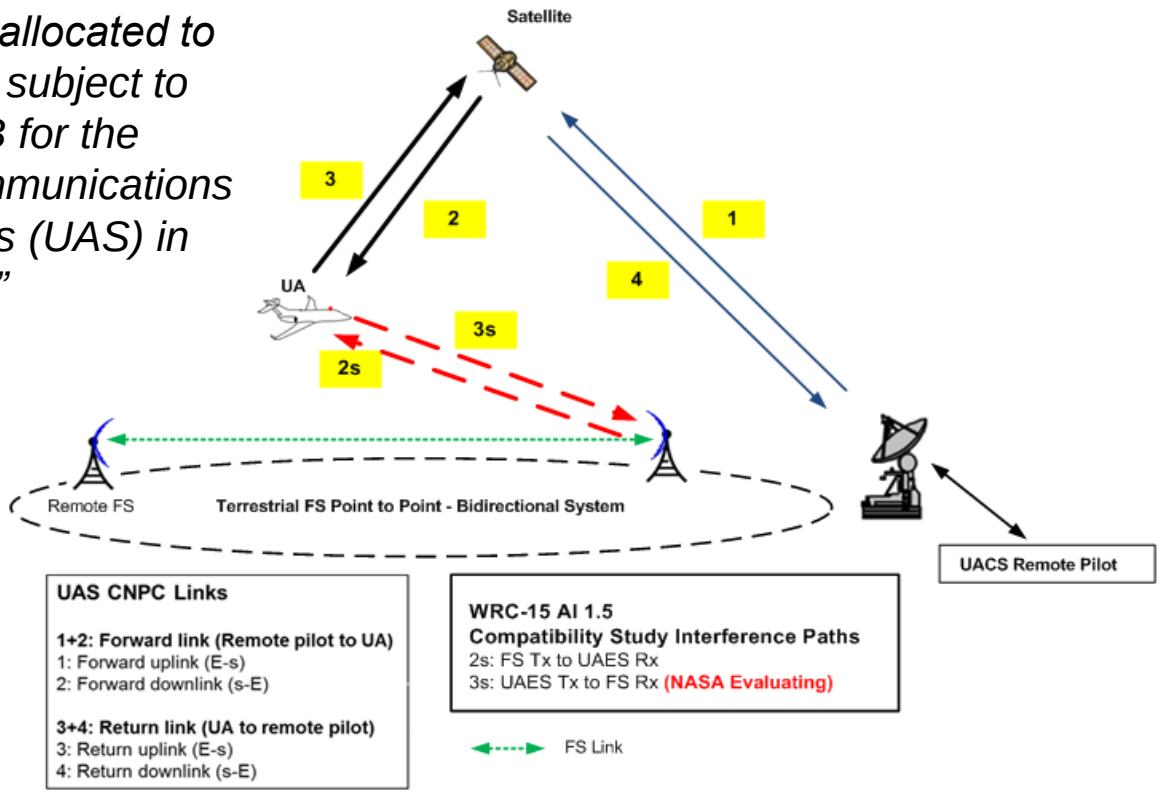
UAS C2 Spectrum

WRC-15 adopted Resolution 155, providing C2 allocations in both Ku-Band and Ka-Band

Sharing studies for 2015 World Radiocommunication Conference Agenda Item 1.5:

> *"the use of frequency bands allocated to the fixed-satellite service not subject to Appendices 30, 30A and 30B for the control and non-payload communications of unmanned aircraft systems (UAS) in non-segregated airspaces…"*

- Studies focused on interference from the UAS into terrestrial systems (link "3s")
- Ku-Band – 14.0-14.5 GHz
- Ka-Band – 27.5-29.5 GHz
- Bands in which Fixed Service allocations exist



Sharing scenario for UAS BLOS C2 in FSS bands.

C2 Subproject Phase 1 Overview

Standards Development

- RTCA Document DO-362, Command and Control (C2) Data Link Minimum Operational Performance Standards (MOPS) (Terrestrial) developed by RTCA Special Committee 228 (SC-228) was published 22 September 2016
- UAS in the NAS laboratory and flight testing, system and network modeling and simulation, system security analysis, spectrum studies and operational analyses contributed to the MPS development and validation
- UAS in the NAS wrote all or part of MOPS sections:
  - Equipment Performance Requirements and Test Procedures – Section 2
  - Common Characteristics – Section 2.2.1
  - MOPS Baseline CNPC Link System Requirements – Section 2.2.2
  - CNPC Link System Manufacturer-Specific Radio Requirements – Section 2.2.3
  - Equipment Performance Verification Procedures – Section 2.4
  - Security Considerations – Appendix D
  - UAS CNPC Link System Operational Capabilities and Implementation Considerations – Appendix F
  - Data Rates – Appendix J
  - Example CNPC Link Budgets – Appendix L
  - UAS CNPC Link Performance (Based on NASA GRC Flight Test Data) – Appendix K
  - MOPS Baseline CNPC Link System – Appendix M
  - Bench Test Data for the MOPS Baseline CNPC Link System – Appendix N
  - Flight Test Data for the MOPS Baseline CNPC Link System – Appendix O
  - Compatibility of TACAN Operations and CNPC Operations using L-Band Signals (Based on baseline radio design) – Appendix P
  - Summary of NASA Air-Ground Channel Measurements and Models – Appendix Q
  - CNPC Link Undesired-to-Desired Signal Ratios (Based on NASA GRC Flight Test Data) – Appendix R

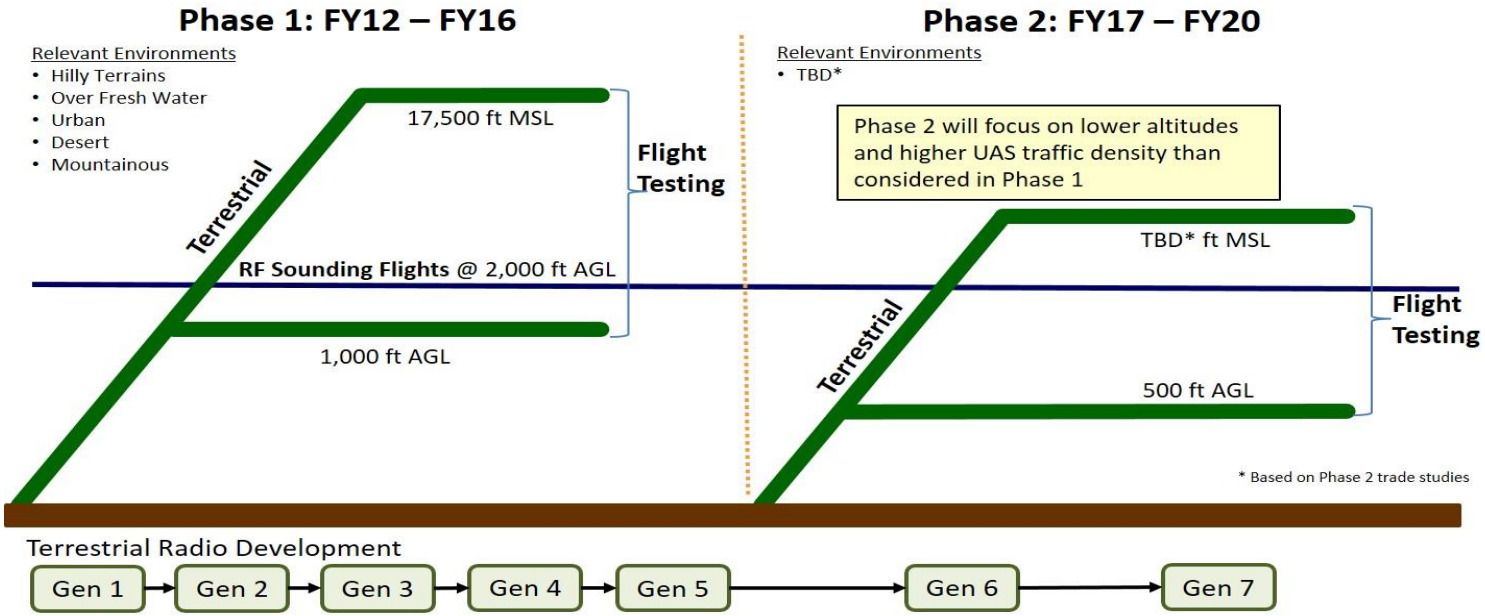
C2 Subproject Phase 2

- Focus on BLOS C2 communications link
- Similar to Phase I:
  - Develop, bench test and flight test the satellite C2 link
  - Provide technical requirements and performance validation for Command and Control (C2) Data Link Minimum Operational Performance Standards (MOPS) (Terrestrial) now beginning to be developed by RTCA SC-228.
- Ku-Band and Ka-Band systems to be tested
  - WRC-15 Resolution 155 allows FSS bands to be used for UAS C2 links in non-segregated* airspace:
  - 10.95-11.2 GHz, 11.45-11.7 GHz, 11.7-12.2 GHz (Region 2), 12.2-12.5 GHz (Region 3), 12.5-12.75 GHz (Regions 1 and 3) and 19.7-20.2 GHz (space-to-Earth)
  - 14-14.47 GHz and 29.5-30.0 GHz (Earth-to-space)
- C-Band study to be conducted, 5030-5091 MHz
- Terrestrial extension of completed MOPS – lower altitudes, higher density
  - Terrestrial radio development and flight testing, similar to Phase 1
  - C-Band only, 5030-5091 MHz

C2 Subproject Phase 2

Terrestrial Extension

- Addresses the smaller, lower altitude, higher traffic density mid-size UAS operational environment
- Technology assessment of signal waveform and access considerations
- Develop additional generations of prototype C2 terrestrial radio system
- Laboratory and flight tests in a relevant flight environment
- Support the extension of the current RTCA SC-228 C2 Terrestrial MOPS



C2 Subproject Phase 2

Ka-Band Satellite Communications

- Develop an appropriate Ka-Band satellite communications-based link between the UAS and the ground control station (GCS) that supports the required performance of the unmanned aircraft in the NAS
  - Ensures that the pilot always maintains a threshold level of control
  - Enables performance validation and development of technical data to support BLOS C2 satellite communications MOPS development
- Flight testing in a relevant environment
- NASA GRC entered into a cooperative agreement with Honeywell International,
  - Use of the Inmarsat Global Express network/Inmarsat I-5 Ka-Band satellite
  - Honeywell's JetWave high-speed satellite communications hardware
- Frequencies defined in WRC-15 Resolution 155: 29.5-30.0 GHz for earth-to-space and 19.7-20.2 GHz for space-to-earth.
- Testing will occur at en-route flight altitudes
- Two types of Ka-Band aircraft satellite communications will be tested
  - Fuselage-mounted phased array
  - Tail-mounted mechanically steerable parabolic reflector

C2 Subproject Phase 2

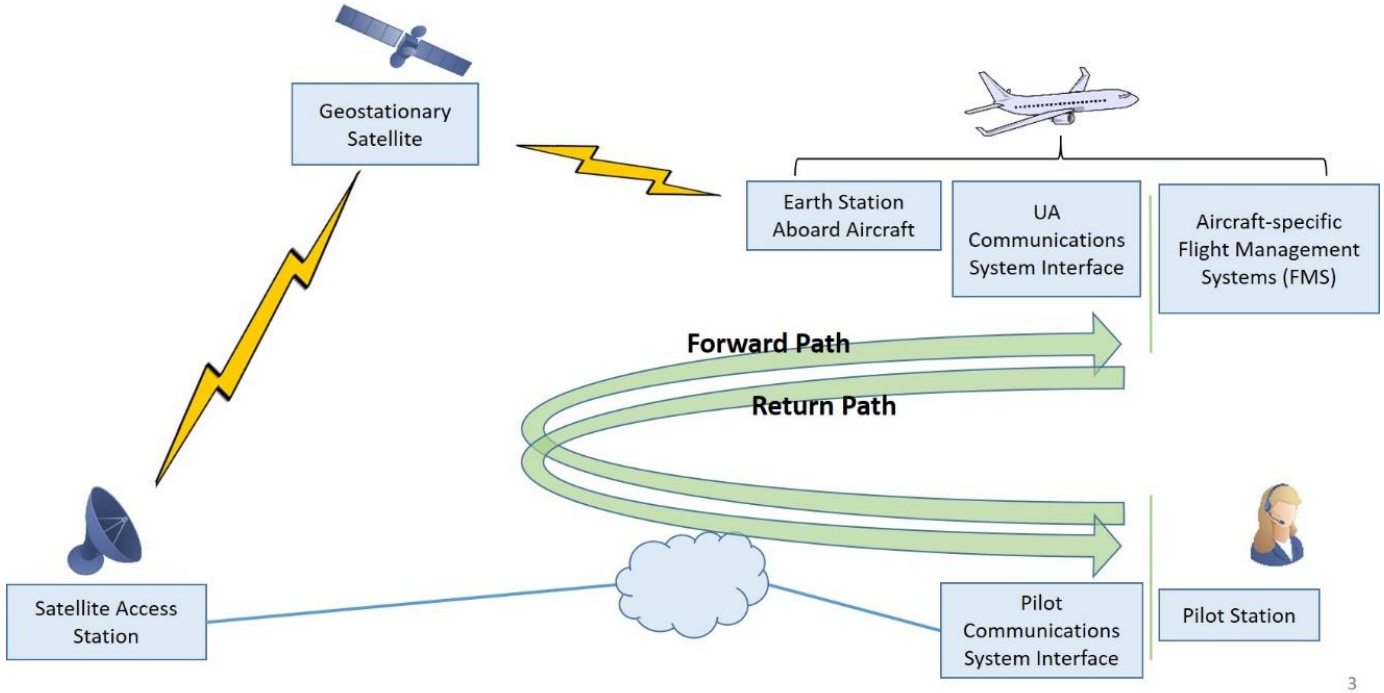
Ku-Band Satellite Communications

- The flight testing described for BLOS C2 satellite communications in Ka-Band will be duplicated in the Ku-Band frequencies
- 14.0-14.47 GHz for earth-to-space, and 10.95-11.2 GHz, 11.45-11.7 GHz, 11.7-12.2 GHz space-to-earth bands applicable globally or in ITU Region 2
- A cooperative agreement partner was not available for Ku-Band testing
  - NASA GRC will develop the required aircraft and ground terminal equipment
  - Identify a suitable Ku-Band satellite network for the flight testing

C2 Subproject Phase 2

Ku- and Ka-Band Satellite Communications

- End-to-end communications latency testing
- Link performance vs. transmit power, data rate, modulation and coding, multiple access scheme, and other parameters.



C2 Subproject Phase 2

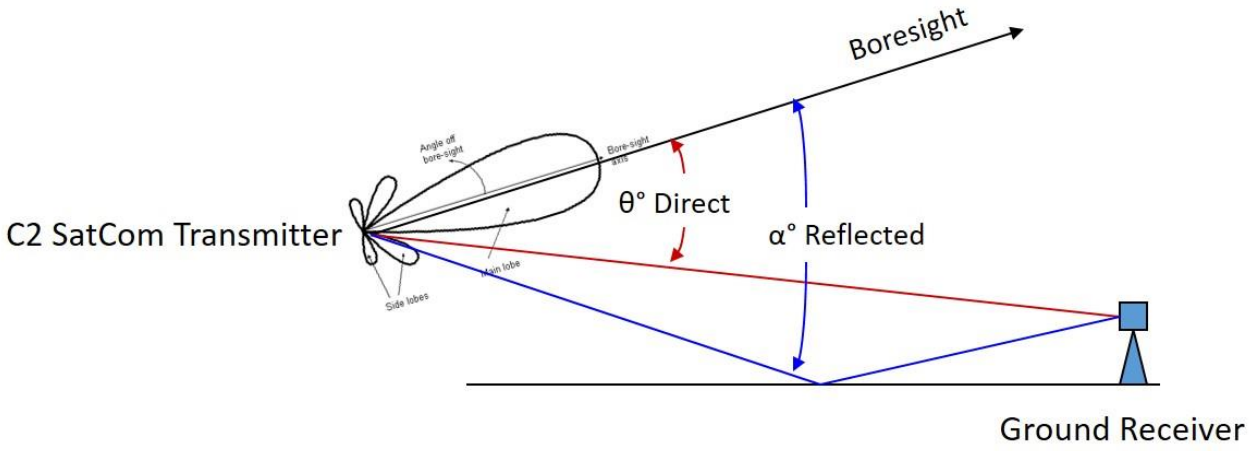
Ku-Band Interference and Propagation

- Resolution 155 allocated Ku-Band C2 spectrum that must share with another co-primary service – Fixed Service (point-to-point and point-to-multipoint digital microwave links)
  - Protection of the Fixed Service from harmful interference from UAS satellite transmitters was (WRC-15) and is (WRC-19) a very contentious issue
  - Resolution 155 requires that a power flux density (pfd) limit be established for the UAS satellite transmitter to protect the Fixed Service
  - The details of the pfd limit are to be decided at WRC-19
- The propagation characteristics of the “interference” channel – the air-ground channel at 14.0-14.47 GHz - have not been well established
- NASA will therefore conduct a propagation measurement campaign to establish propagation characteristics and channel models
  - Flight test campaign similar to Phase 1 (960-977 MHz and 5030-5091 MHz)
  - Development of channel models appropriate for interference assessment

C2 Subproject Phase 2

Ku-Band Interference and Propagation

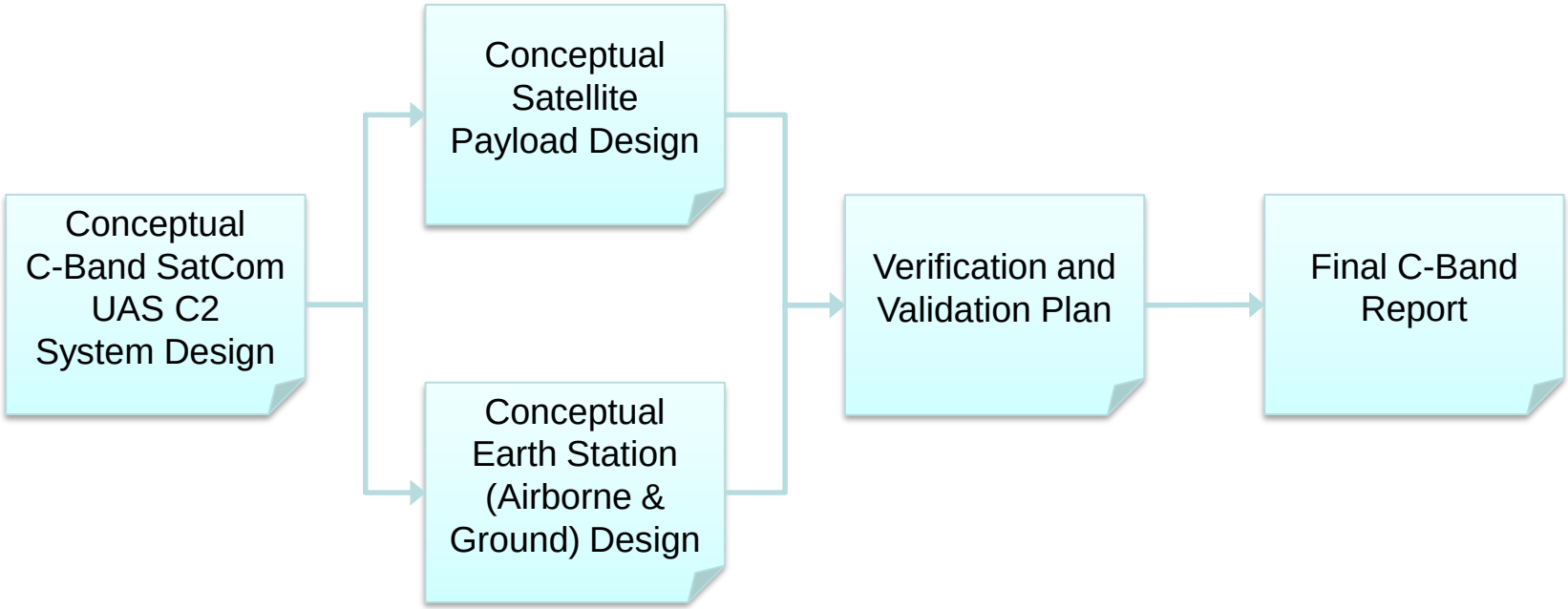
- Initial experiment design:
  - Omni-directional antenna on the bottom of the aircraft
  - 2 ft. parabolic receive antenna on the ground, simulate Fixed Service receive station
  - Broad beamwidth horn antenna to capture larger range of transmission
- See previous presentation “UAS Satellite Earth Station Emission Limits for Terrestrial System Interference Protection”



C2 Subproject Phase 2

C-Band Satellite Communications

- An AMS(R)S allocation in C-Band covers the 5030-5091 MHz band and would also be suitable for BLOS C2 satellite communications.
  - C-Band will be studied to provide technical data for MOPS development
- However there are no existing satellites operating in this band
  - No flight testing is possible
- The C-band activity will therefore be study-based



UAS C2 Link – from LOS to BLOS

Summary

- NASA's UAS in the NAS Project's C2 Subproject has entered Phase 2
- Phase 1 (2012-2016) emphasized LOS C2 terrestrial link, development of technical data for supporting the completion of C2 Terrestrial MOPS
  - L-Band/C-Band air-ground channel; C2 prototype radio development and testing; system and network modeling; security analysis; sharing studies for BLOS spectrum allocation; MOPS document DO-362
- Phase 2 (2017-2020) emphasizes BLOS C2 satellite communications
- As with Phase 1, technical data will be developed to support RTCA SC-228 development of BLOS C2 satellite communications MOPS.
- Terrestrial extension of the C2 Terrestrial MOPS (i.e. DO-362)
  - Smaller, lower altitude, higher traffic density mid-size UAS operations
  - Tech assessment, C2 radio development, laboratory and flight testing
- Ku and Ka-Band C2 satellite link development and testing
  - Cooperative agreement with Honeywell for Ka-Band
  - NASA GRC in-house development and testing at Ku-Band
- Ku-Band air-ground channel model development for interference modeling
- C-Band C2 satellite link study, develop technical performance information.

Thank you!

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