Engineering, Operations & Technology
Boeing Research & Technology

UAS CNS Architectures for Uncontrolled Airspace

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eprint
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Project Background

NASA Contract NNA16BD84C

- **NASA Safe Autonomous Systems Operation (SASO) – Communications, Networks and Surveillance (CNS) for Unmanned Air Systems (UAS)**
- **Reliable and Secure CNS and Networks (RSCAN) project**
- **“Revolutionary and Advanced universal, reliable, always available, cyber secure and affordable Communication, Navigation, Surveillance (CNS) Options for all altitudes of UAS operations”**
- **18 month performance period**
  - **Contract signed August 17, 2016**
  - **Kickoff meeting (work begins) September 17, 2016**
  - **First midterm review February 17, 2017**
  - **Second midterm review August 17, 2017**
  - **Final Review February 26, 2018**
  - **Final report March 17, 2018**

Results

- **Architectures for UAS CNS in Controlled Air Space**
  - Consistent with NASA/FAA/ICAO ATM vision
  - Cooperation with manned aviation
  - Assumes remote pilots - either stationary or mobile – with increasing levels of autonomy
  - Builds security into the architecture from the beginning to mitigate threats to safe operations
- **Architectures for UAS CNS in Uncontrolled Air Space**
  - Consistent with NASA UTM vision
  - Operations must not interfere with controlled air space
  - Increasing role for law enforcement
  - Remote pilots coordinate with UTM Service Suppliers (USS)
  - Remote pilots control UAS enclaves (could control more than one UA at a time)
  - Eventual pilot-less operations with increasing levels of autonomy

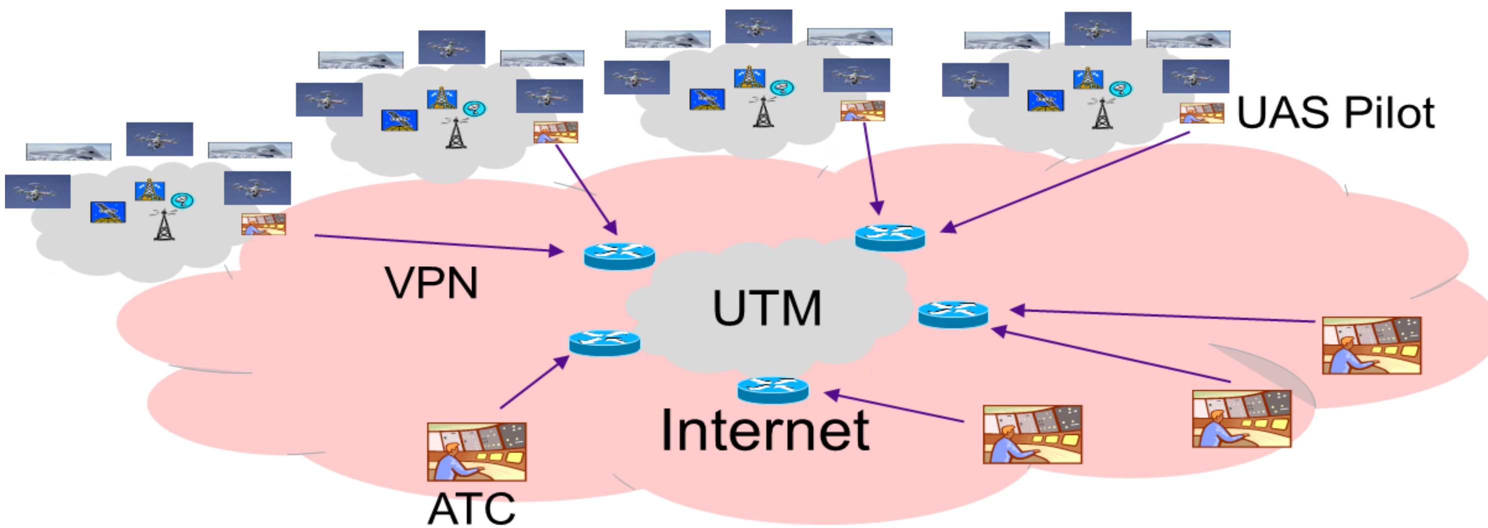
Futures

- **Project concluded**
  - CNS Final Report Submitted 3/16/2018
- **Seek additional publication opportunities**
- **Engage industry forums (ICAO, RTCA, IETF)**
- **Lead the transition:**
  - remotely-piloted UAS with mobile remote pilots
  - increasingly-autonomous operations
  - eventual fully-autonomous operations
- **Investigate opportunities for continuation beyond end of project**
  - UAS in the NAS Systems Integration and Operationalization (SIO)
  - UTM Pilot Program (First Workshop March 15, 2018)
  - Other NASA/FAA opportunities

Communications Networks

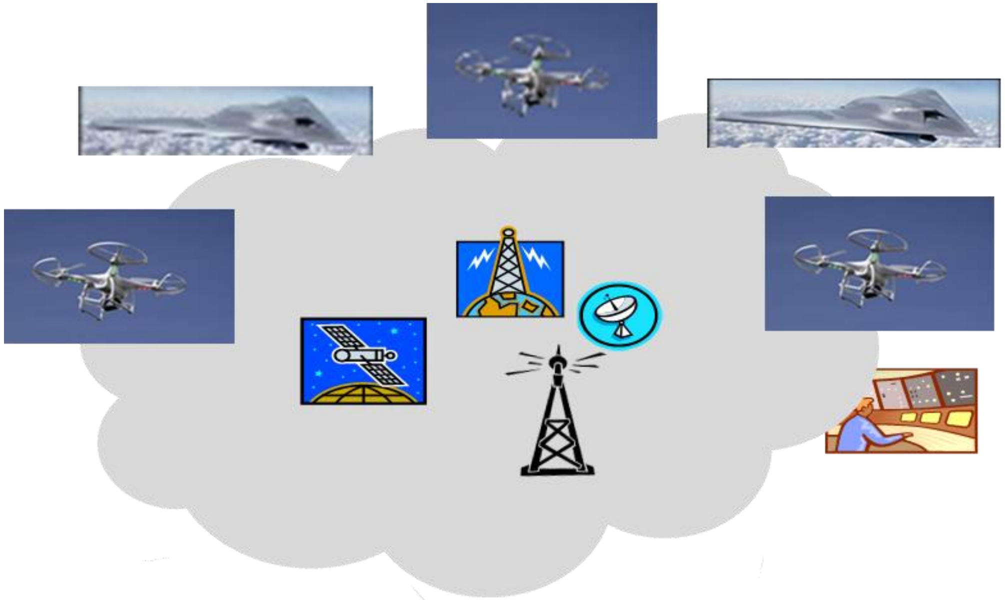
The UTM Communications Network

- sUAS operating in uncontrolled airspace require continuous CNS **Situational Awareness (SA)** in a secured service over the Internet called **"The UTM"**
- **Command and Control (C2)** messaging from UTM Service Suppliers (USS) on **Manage-By-Exception (MBE)** basis (active management does not scale)
- MBE means that sUAS are required to operate in compliance with **FAA PART107**, and only those sUAS deviating from [PART107] guidelines would be subject to preemptive and/or corrective UTM C2 directives



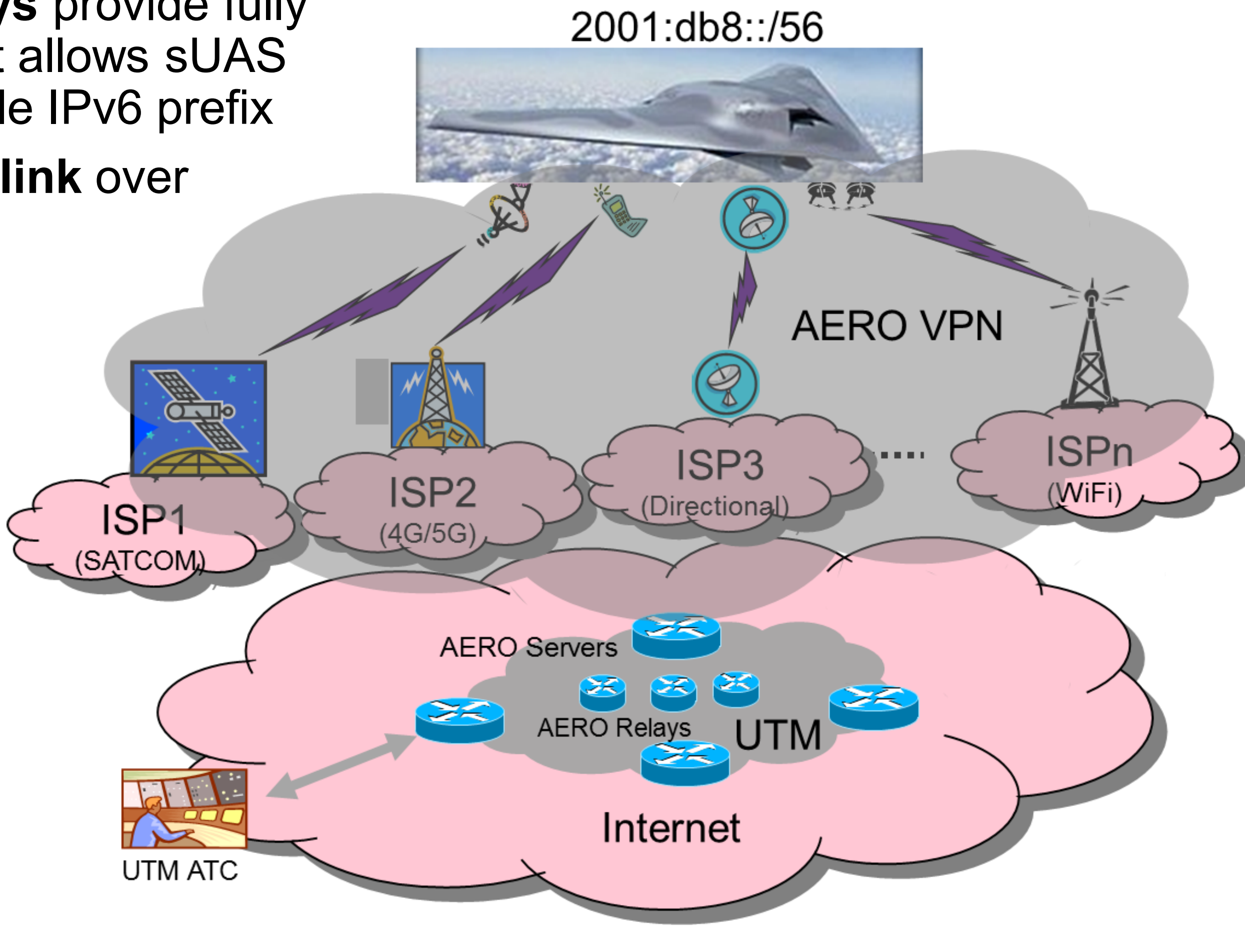
Small Unmanned Air Systems (sUAS)

- sUAS include Small Unmanned Aircraft (sUAs), Remote Pilots and Communications Data Links.
- UTM must scale to millions of connected sUAS enclaves and end systems – **need Internet Protocol version 6 (IPv6) addressing to support scale**
- IPv6 /32 prefix (e.g., 2001:db8::/32) can accommodate up to 4 billion /64 subnet prefixes (e.g., 2001:db8:1:2::/64)
- With a /64, each sUAS can include countless addressable entities in an **"Internet-of-Things"**



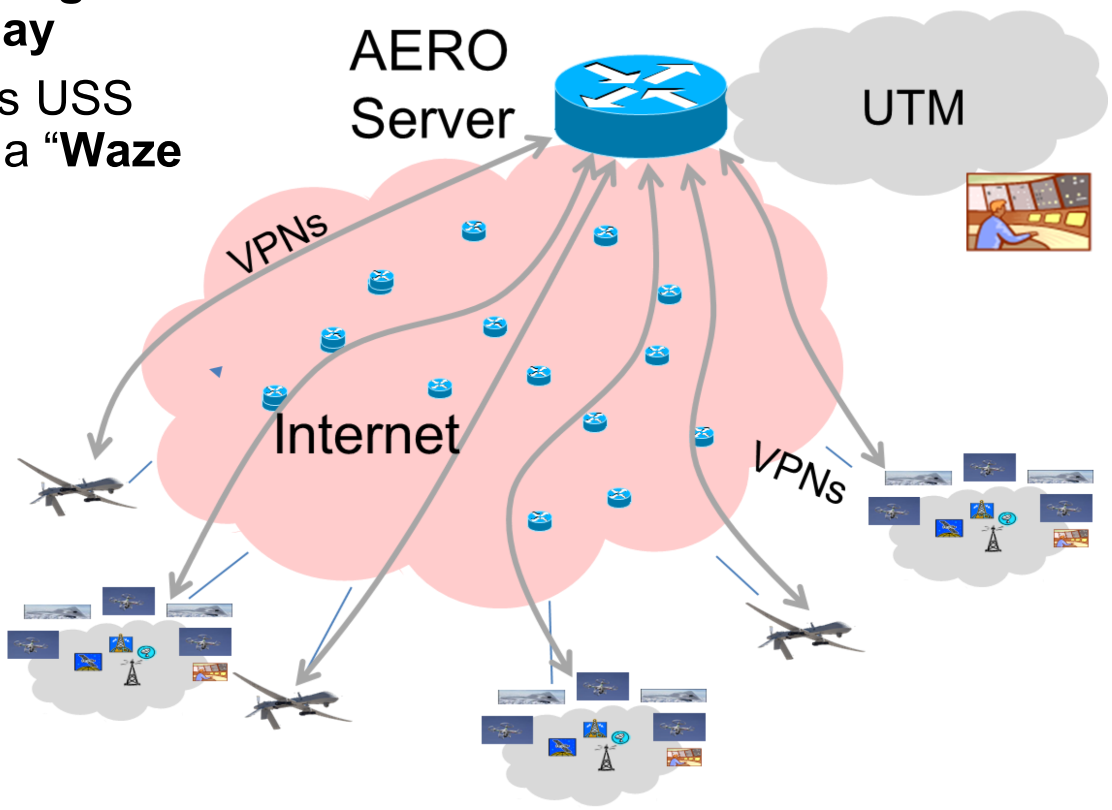
AERO Networking Services for the UTM

- Need an overlay network over the Internet
- USS C2, sUAS connect to to the UTM via **secured VPNs** using the **AERO service**
- **AERO Servers and Relays** provide fully mobile routing service that allows sUAS **Clients** to maintain a stable IPv6 prefix
- AERO provides true **multilink** over available data links



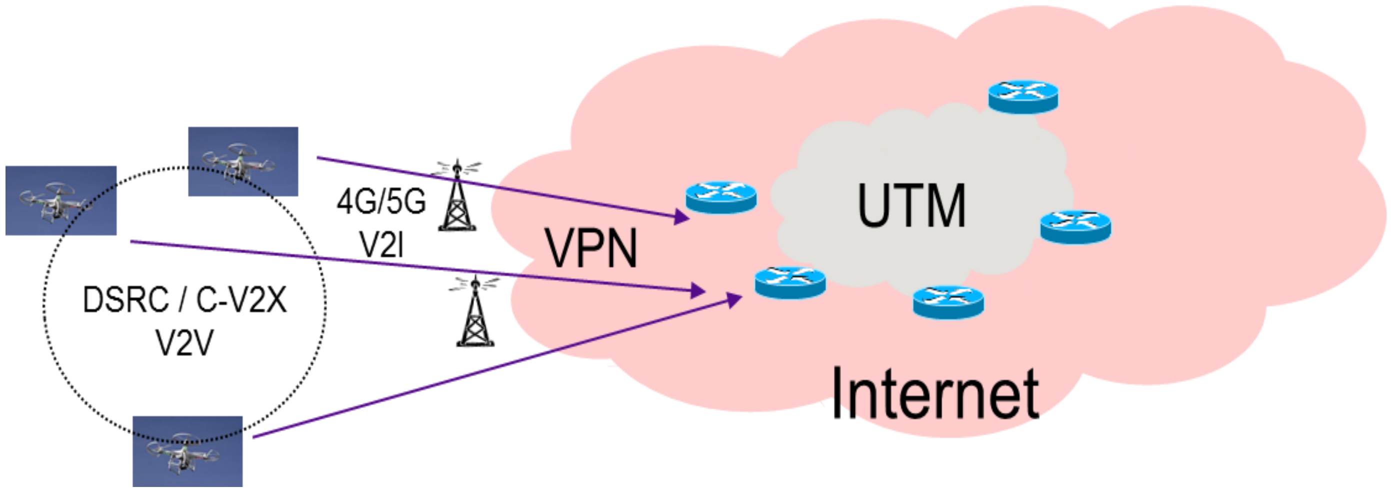
The AERO VPN Model

- sUAS and fully-autonomous UAs form **Virtual Private Network (VPN)** secured links over the Internet
- Internet-based secured AERO Servers connect to the **UTM global enterprise network overlay**
- UTM routing system allows USS MBE and pervasive SA in a "**Waze for UAs**" service



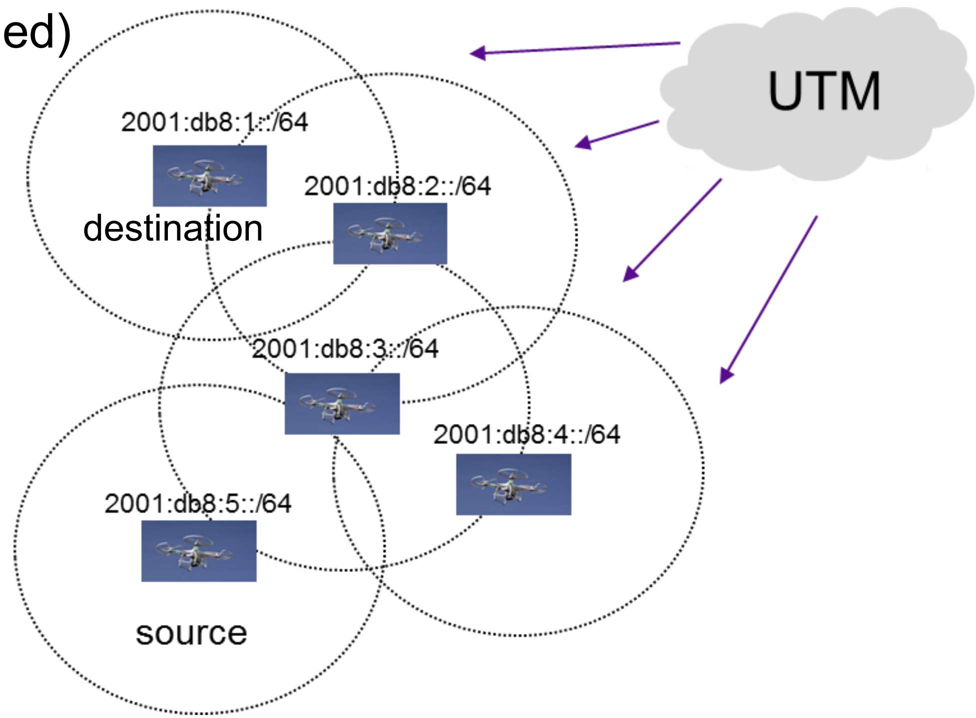
sUAS Vehicular Ad-hoc Network (VANET)

- each sUAS will have both Vehicle-to-Infrastructure (V2I) (e.g., 4G/5G) and Vehicle-to-Vehicle (V2V) data links
- IEEE and 3GPP have specified data link services for automobiles and other ground vehicles (DSRC; C-V2X)
- These same services can be adopted for sUAs in the UTM even for small vehicles with limited Size, Weight and Power (SWAP) profiles
- sUAS **coordinate** with the UTM via VPN and **collaborate** with one another via short range omnidirectional



Multihop V2V Communications

- **source** sUAs sends messages to first-hop neighbors, which repeat them until they reaches the **destination**
- Ideally suited for multicast applications (e.g., V2V SA sharing)
- especially important in VANETs in which communications opportunities may be based on random (rather than planned) contact opportunities



Communications Data Links

Wi-Fi: Status

- **Applicability: Small UASs within a few km range**
- **Advantages:**
  - Universal availability. Easily developed and tested.
  - License exempt band
  - High-Throughput
  - Low cost
- **Disadvantages:**
  - Short Range: 300 m typical max
  - High power consumption $\Rightarrow$ 20 minutes flight time
  - Mostly proprietary APIs $\Rightarrow$ No interoperability among UASs
- **Product Status: Currently used in a majority of sUASs**
- **Yet to be Done: Interoperability**

ZigBee: Status

- **Applicability: Small UASs, pilot-UAS communications**
- **Advantages:**
  - License exempt band
  - 900MHz ⇒ Longer Reach than WiFi
- **Disadvantages:**
  - Mostly proprietary variations (XBee Pro, 3DR, RFD900) used
- **Product Status: Widely used**
- **Yet to be Done: Interoperability**

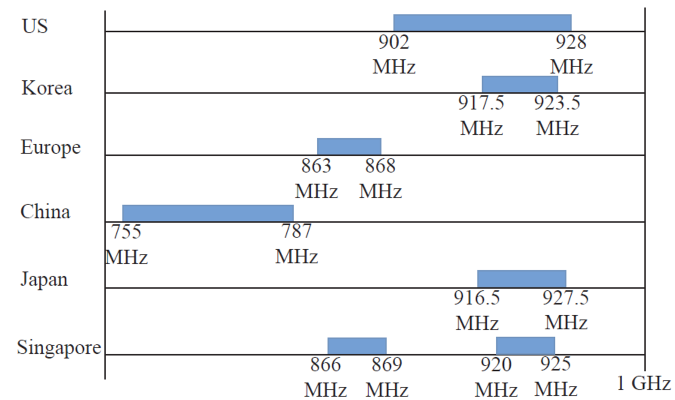
Bluetooth: Status

- **Applicability: 30m Reach**
  Swarms and Follow me applications
- **Advantages:**
  - Low Cost
  - License Exempt Band
- **Disadvantages: Very short range**
- **Product Status:**
  - Used in many products.
  - Standard version used.
- **Yet to be Done: N/A**

4G/5G Cellular: Status

- **Applicability**:
  - In competition with Satellites in many areas.
  - Both Small and Large UASs
- **Advantages**:
  - Service providers
  - Existing infrastructure
- **Disadvantages**:
  - Available only along highways
  - Available only in populated areas
  - Tower antenna pointing downwards
- **Product Status: Demonstrations and trials**
- **Yet to be Done: Wide-scale use**

Adopt IoT Data Links



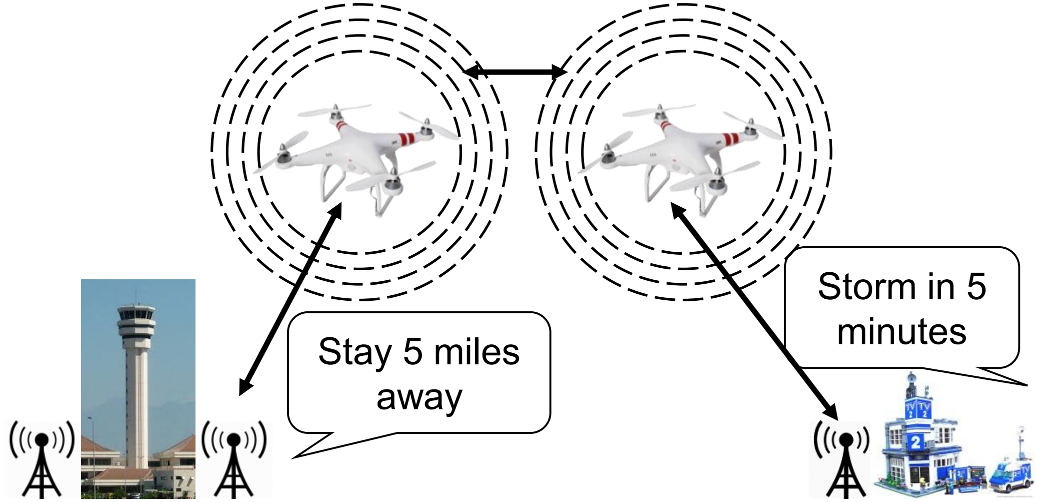
- **Internet of Things (IoT) Data Links:**
  - Much longer reach than WiFi
  - Extremely power efficient
  - Small Size
    ⇒ **Ideal SWAP** for UAS
- ***IEEE 802.11ah***
  IEEE Standard for Low-Rate Long-Range IoT Applications
  Aka "WiFi HaLow" **by WiFi Alliance.**
- **Sub-GHz frequency: 700-900 MHz**
  ⇒ Longer range than 2.4 GHz,
  Less congested, better penetration
- **Media Access Control is made more efficient by reducing header, aggregating acks, and speed frame exchanges**
- **Save energy by allowing stations and Access Points to sleep**
- **Potential solution for small UASs within a 20-30 km range**

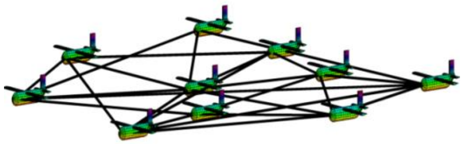
Adapt Vehicular Standards for UAS

- **Vehicular area networks (VANETS) are being designed for automobiles**
- **Allow autos to be notified of important information and for collision avoidance**
- **UASs have SWAP limitations which are stricter than autos: Lower power, larger speed, smaller size, longer distance $\Rightarrow$ Need to adapt**
- **Two upcoming VANET Standards:**
  - Dedicated Short Range Communications (DSRC)
  - Cellular Vehicle-to-X (C-V2X)

DSRC Applications for sUAS

- **Broadcast**: Traffic (area temporarily blocked), weather (storm coming), emergency, road/airway conditions, …
- **Geocast**: Within an area. Accidents, prohibited areas
- **Dynamic Geo-Fencing**: Away from crowds, emergency
- **Clustering**: Within a specified group. Police, Fire, Safety





Cellular Adaptation of DSRC (C-V2X)

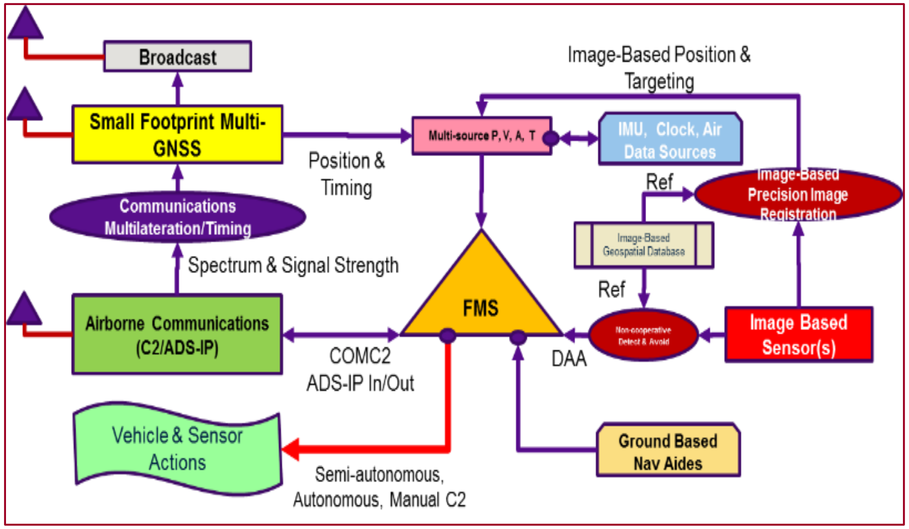
- **Cellular Vehicle-to-X (C-V2X) is designed to take over the VANET Market**
- **LTE-V2X is already in Release 14 (March 2017)**
- **Claimed Enhancements:**
  - Bigger channels ⇒ More throughput
  - Improved channel estimation ⇒ Higher Speed
  - Better modulation ⇒ Longer distance
  - Centralized (Tower) scheduling ⇒ Improved efficiency
  - PHY (HARQ) retransmission ⇒ Improved reliability
  - Single Carrier FDM instead of OFDM ⇒ Higher transmit power ⇒ Longer Range
- **Issue: Vehicle-to-vehicle communication cannot use carrier's spectrum. Need to use DSRC spectrum.**

Navigation

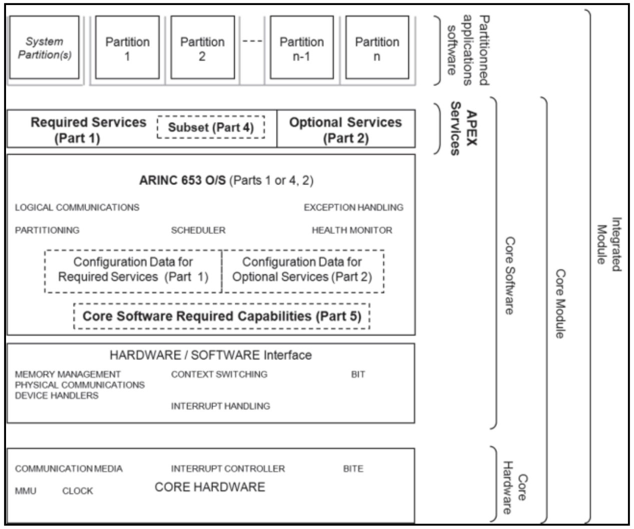
sUAS Navigation Architectural Framework

– Advancements in accurate navigation position & timing references are critical enabler for improved coordinated communications (COMC2), surveillance processing (i.e. TCAS, ATC), and surveillance broadcasting (i.e. ADS-B, ADS-IP). Disciplined activities are needed to:
  - Design for certification (i.e. ARP4754)
  - Design for synchronization (i.e. distributive position & timing)
  - Design for reconfiguration (i.e. hardware & software)

Integrated Modular Avionics

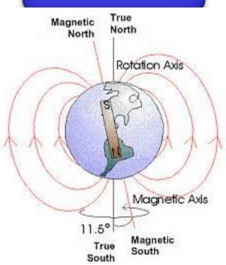


Software Virtual Machine Computing

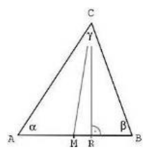


Position & Timing Solution Space is Broad

MAD

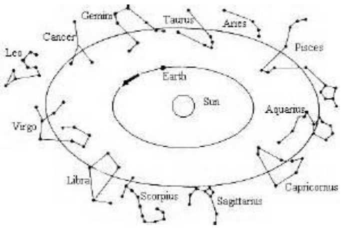


SoP Location



VOR/DME /LORAN

Star Tracker



Terrain Mapping

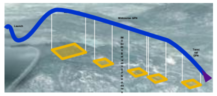
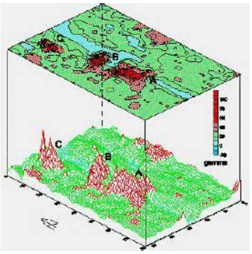
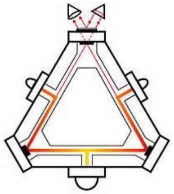


Image Registration

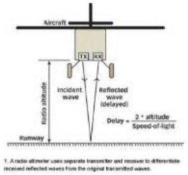


Precision IMU



Non-GPS Satellites

LPI Altimeter



Precision Clock

Position & Timing Solution Space Mapping

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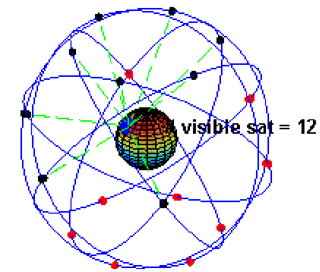
Position & Timing Requirements / Solution Mapping																
Requirements	**Information**				**Attributes**						**Vulnerabilities**			**Other**		
Solutions Space	**Lat/Long**	**Altitude**	**Attitude**	**Time**	**Long Term Stability**	**All Weather**	**Global**	**All Altitude**	**24/7**	**Passive or LPI**	**Survivable**	**Anti-Jam**	**Anti-Spoof**	**No Off Platform Support**	**Cyber Secure**	**Comments**
GPS/GNSS	A	MSL	Aid	Ta	✓	✓	✓	✓	✓	✓	?		?		✓	Trans Align, Almanac, Ephem
Precision IMU	R	MSL	Rate		Drift	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	Transfer Alignment
Altimeter		AGL	Aid		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Air Data		Baro	Aid		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	Air Speed
Star Tracker	A	MSL	Attitude		✓	Clouds	✓	Low	✓	✓	✓	✓	✓	✓	✓	Space Object Tracking
Non-GPS Satellites	A	MSL	Aid	Ta	✓	✓	✓	✓	✓	✓	?		?			Iridium, et al
Signals of Opportunity	A/R	MSL/AGL	?		✓	✓				✓	Turn Off		Relocate			
Magnetometer (MAD)	North		Heading		✓	✓	Poles	✓	✓	✓	✓	?	✓	✓	✓	Transient Distortions
VOR/DME/LORAN	A		Aid		✓	✓		✓	✓							
Precision Clock				Ta	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
EO/IR Image Registration	A	MSL	Aid		✓	Fog/Rain	1	✓	✓	✓	✓	✓	✓	✓	✓	Coverage / Mapping Time
LIDAR	A	MSL	Aid		✓	Fog/Rain	1	High	✓	LASER	✓	✓	✓	✓	✓	
LADAR	A	MSL[1]	Aid		✓	Fog/Rain	1	High	✓	LASER	✓	✓	✓	✓	✓	
Hyperspectral	A	MSL[1]	Aid		✓	Fog/Rain	1	High	✓	✓						

1 - Desert, Lake, Ocean, Plains & Tundra Issues

Key	
Position - Absolute Lat/Log	A
Position - Relative Lat Long	R
Altitude - Above Ground Level	AGL
Altitude - Mean Sea Level	MSL
Altitude - Indicated (Baro)	Baro
Time - Absolute	Ta
Time - Relative	Tr

Global Positioning System (GPS)

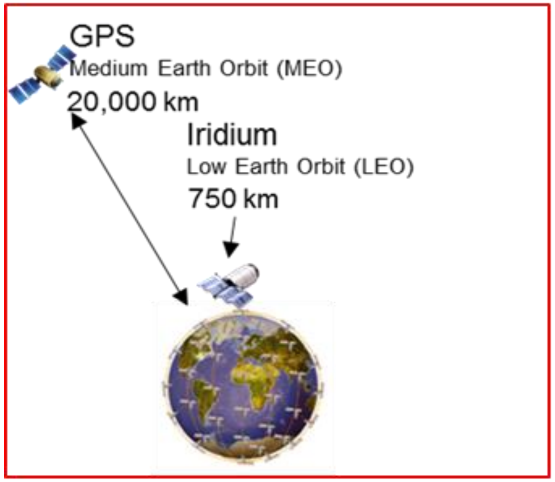
- **Global Positioning System (GPS) is a space-based satellite navigation system providing location and time information in all weather conditions, anywhere on or near the Earth**

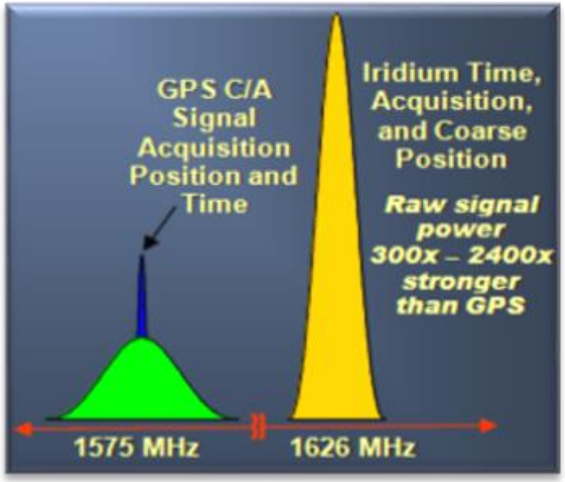


- GPS Information → Latitude Longitude (Accurate) | Altitude | Accurate Time | Long Term Accuracy
- Attributes → All Weather | Global | All Altitude | 24/7 | Passive (LPI)
- Vulnerabilities → Survivable | Anti Jam | Anti Spoof

Example GPS-Like SoP source
LEO Space Vehicle (SV) Constellations

- **A signal of opportunity (SoP) communication source of navigation and timing which operates within the low earth orbital constellation called Iridium made up of 66 satellites.**
- **There has been a number of research efforts conducted proving low earth orbital signals provide greater coverage and even improved navigation accuracy over traditional GPS signals due to the signal strength being approximately 300 to 2400 times stronger than GPS.**
- **Iridium has the ability to provide positioning information using only one satellite vehicle source due to the rapid movement of each satellite.**
- **Additionally, the Iridium signals support deep indoors navigation and timing which is very useful for sUAS operating in dense urban areas**





Surveillance

ADS-IP

ADS-IP

- Centralized, automated, and cooperative surveillance system which uses IP channels to manage the data interchange between UAs and a server on ground (**ADS-IP Server**), and between such server and other actors such as an automatic traffic supervisor or the fleet owner.
- With a determined rate, each UA sends its surveillance data to an ADS-IP server. Surveillance data includes: UA ID, location (latitude, longitude, altitude), air speed, intent…
- ADS-IP servers act as the core of the system, gathering and storing all the navigation data transmitted by the UAs and distributing it accordingly to the needs of each actor.
- Since the range of ADS-IP is not determined by the attenuation of the signal transmitted (as it is with traditional surveillance systems), it has to established by defining areas of interest.
- **ADS-IP Directory Servers** to determine the ADS-IP server to be used by each UAS. They are repositories of ADS-IP Servers which also store their area of service. Each ADS-IP server is registered in a primary ADS-IP Directory Server. They implement a geographical and hierarchical service area. Reliability is provided with the implementation of secondary ADS-IP Directory Servers.

uADS-IP

uADS-IP

- Similar functionalities as ADS-B.
- Optimized to operate in a different context:
  - Lower range.
  - Higher UA density.
  - No interference with ADS-B.
- Makes use of an existing V2V communication standard:
  - e.g.: DSRC / 802.1p
- Encryption capabilities:
  - Symmetric encryption for broadcasted surveillance data (RF).
  - Use of PKI to generate key distribution/renewal service credentials.
  - Key distribution/renewal through an Internet connection.
  - Low rate of key renewal (hours, days…) to enable the operations of UA with no Internet connectivity (requires key update before the operation)
- The same principles could be implemented in a future encrypted ADS-B (internet connectivity needed).

Non - Cooperative surveillance systems

	Range	Position accuracy	Classification	Not-connected UAS detection	RPAS/connected detection	Detection under low visibility conditions	Cost
Human surveillance	●●	●●●	●●●●●	✓	✓	✗	●●●●●
Passive Electro-optical/Infrared	●●●	●●●●	●●●●	✓	✓	✗	●●●
Acoustic	●	●●	●●	✓	✓	✓	●●
Active Radar	●●●●	●●●●	●	✓	✓	✓	●●●●
Electromagnetic signature analysis	●●●●	●●	●●●	✗	✓	✓	●●

Cooperative surveillance systems

	Range	Position accuracy	Classification	Detection Reliability	Detection under low visibility conditions	Cost	Security	Efficiency
ADS-B	●●●●	●●●●●	✓	●●●●●	●●●●●	●●●	●	●●●
µADS-IP	●●●	●●●●●	✓	●●●●●	●●●●●	●●●	●●●●	●●●●●
ADS-IP	●●●●●	●●●●●	✓	●●●●●	●●●●●	●●●●●	●●●●●	●●●●●
Encoded light signaling	●●	●●●	✓	●●●	●	●●	●	●●
Light signaling	●●	●●	✗	●●●	●●	●	●	●●
Acoustic signaling	●	●	✗	●	●●●	●	●	●

ADS-B vs µADS-IP vs ADS-IP

	ADS-B	µADS-IP	ADS-IP
Range	**< 150 NM**	< 1 NM	**Fully customizable**
Update interval	< 1s	**< 0.5 s**	Depends on the DL 0.5 s - 2 s
Reliability	Higher. V2V communication	Higher. V2V communication	Lower. **It depends on infrastructure (internet)**
Cost (maintenance)	No DL required	**Not strictly DL required.** Automatic key renewal if DL available.	DL required.
Cost (deployment)	No infrastructure required	Infrastructure required. Key distribution/renewal server.	Infrastructure required. ADS-IP server.
Security	**No security layer.**	Slightly lower. Key valid during hours/days.	Slightly higher. No key distribution required.
UA density capability	Optimized to high range requirements (no density).	Fixed bandwidth sharing. Optimized for high density /low range requirements.	Does not depend on a specific band of operation

Light and acoustic signaling

Signaling

- Very short range, slightly higher in the case of light signaling.
- Not able to transmit any data to the ground.
- Beacons to let know the controller their presence.

Modulation

- Modulation pattern to encode and broadcast some limited parameters
- Could also be applied to establish a ground-to-air communication channel to transmit very specific orders.
- In this case, the person to transmit the order would know the unique aircraft ID (received by light signaling) and could get remote and secure access to an emergency code (specific for the unique aircraft ID) that could be transmitted to the sUAS (by means of light signaling).

Backups