Field Research Vehicles

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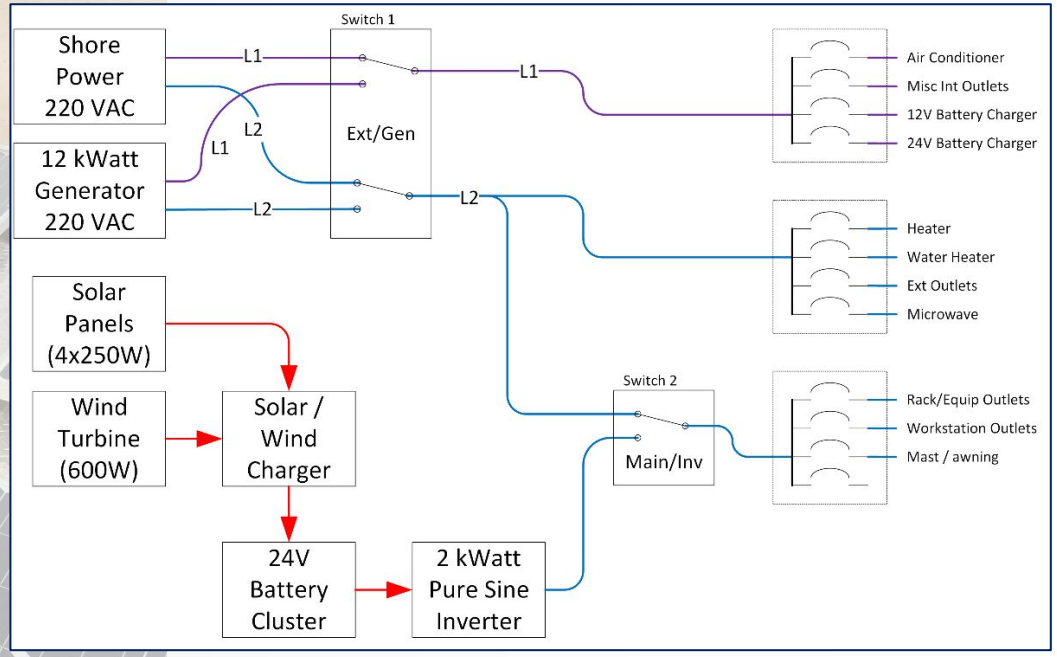
- Two identical 9-ton vehicles
  - Operational in June 2015 following 2013 DURIP award
  - Ford F550 chassis, 42’ mast, equipment bay, stabilizer jacks, awning, roof mounting rails, 12kW generator, battery / inverter / solar operation
- Supporting research and experimentation in
  - Wireless communications
  - Radar
  - Intelligence/surveillance/reconnaissance (ISR)
  - Electronic warfare (EW)
  - Active/passive sensing

AC/DC power systems

- Three AC operating modes
  - Shore power (220 VAC)
  - Generator power (12 kW)
  - Battery / Solar / Wind power (2 kW)
- Switches in vehicle load center direct power from the desired source to load
- 24 VDC and 12 VDC outlets in vehicle power DC electronics such as software radios at top of mast
- Battery / Solar / Wind mode
  - Batteries drive 2 kW inverter to power equipment bay and workstations
  - Solar panels and/or wind generator simultaneously charge batteries
    - Four solar panels provide up to 1kW
    - Wind generator provides up to 600 W
  - This is primary operating mode used in our experimentation



Primary mast

- 42 foot telescoping, pneumatic mast
  - Locking collars (ensure stable height during experiment)
  - Fittings for attaching guy lines
- Masthead
  - Two-axis rotor (pan/tilt), remotely controlled from vehicle
  - Horizontal mounting bar for antennas and camera (above rotor)
  - IP camera displays live feed of antenna boresight
  - Masthead provides additional mounting for custom boxes (e.g., software radios) (below rotor)
- Nycoil connectivity: masthead to vehicle
  - 36 optical fibers (10Gbe, RF-over-fiber, etc)
  - 2 RF coax (10 MHz ref, PPS)
  - 1 CAT6 Ethernet (IP Camera)
  - 4 AWG10 copper wires: 12VDC, 24VDC
  - 2 multi-conductor cables: rotor pan/tilt control

Additional mounting locations

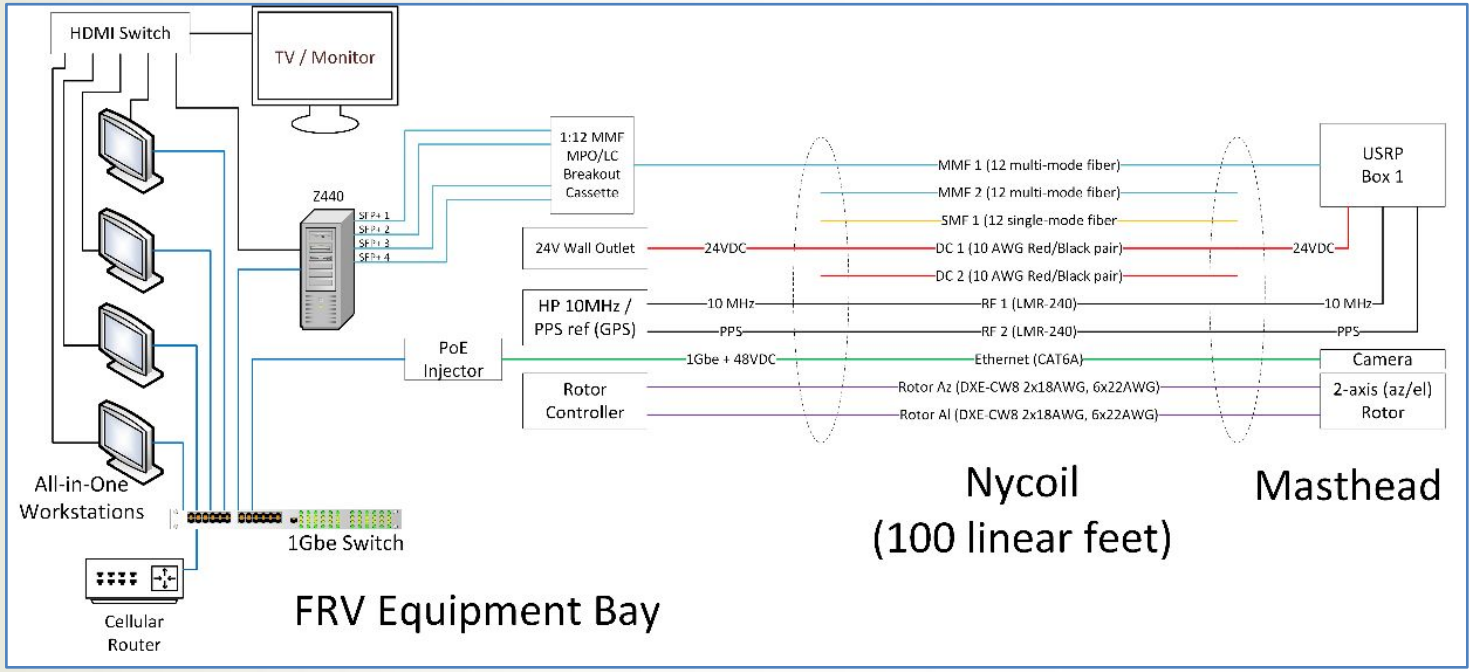
- Roof rails (both sides of vehicle) provide additional mounting for antennas / equipment
- Two feed-through panels and three cable ports connect exterior equipment to instrumentation inside the vehicle
- Wind generator mast doubles as secondary antenna mount (see previous slide)

Vehicle interior

- Four all-in-one touchscreen workstations (with associated seating & desktop space)
- Large 50” UHD TV monitor for viewing any of the workstations
- Equipment bay
  - Holds two 14U portable cases (19” rack)
  - Permanent overhead 10U racks (18” depth)
    - Octoclock-G time/frequency reference
    - rotor dual-axis controller
    - cellular modem / 1Gbe switch
    - network attached storage (NAS)
  - Rear-door access to all racks
- Audio features include two internal and two external speakers and Bluetooth car stereo unit

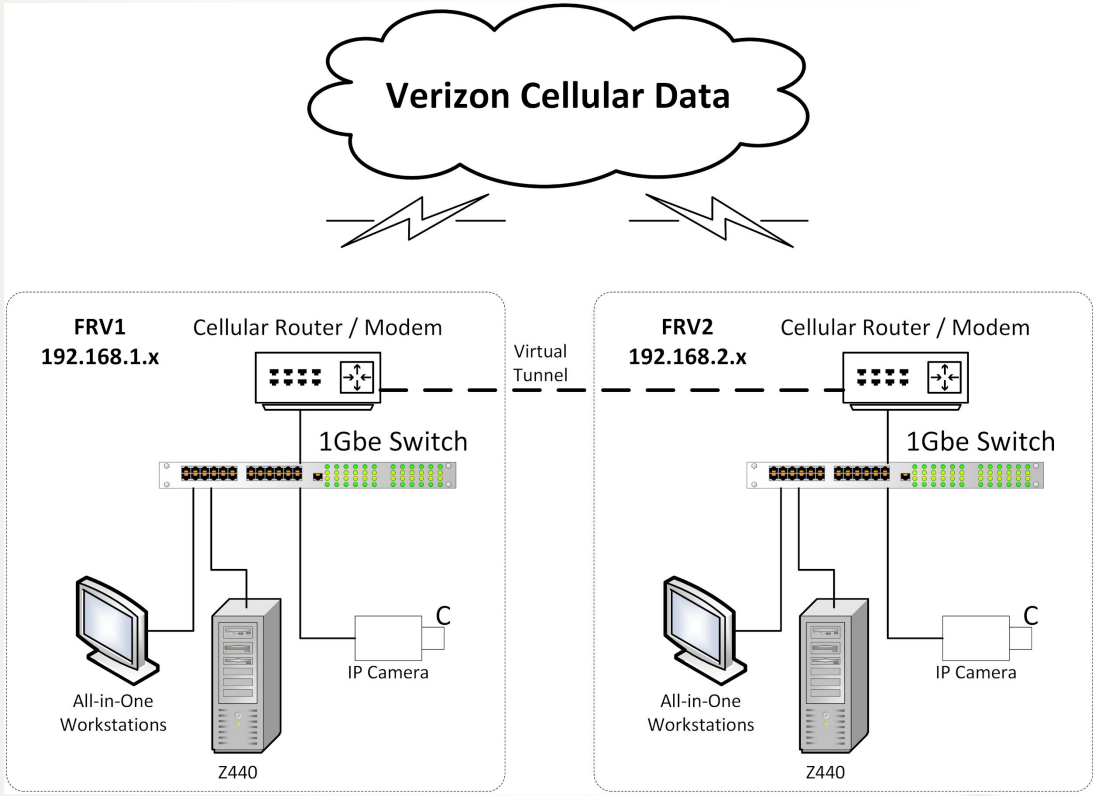
Networking and system connectivity

- Internal 1Gb Ethernet network with RJ45 jacks throughout the vehicle for connecting workstations and equipment
- Dedicated 10Gb Ethernet links to equipment at top of mast
- Powerful Z440 Linux workstation for USRP control and data streaming / recording
- Cellular data modem provides mobile Internet capability



FRV-to-FRV networking

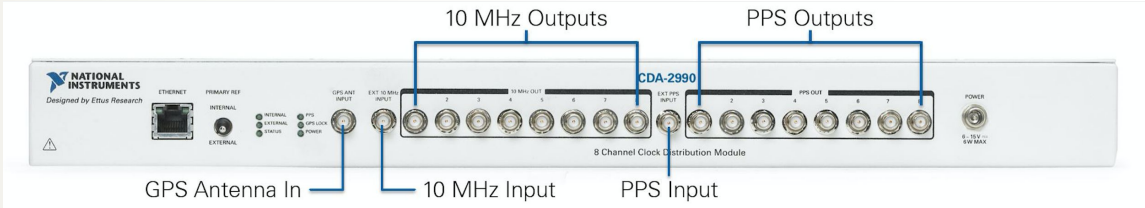
- Cellular router / modem in each FRV provides connectivity to the internet as well as tunneling between the vehicles
- The tunnel provides a private network including the IP subnets of both vehicles such that computers in one vehicle can communicate over this private network to computers in the other vehicle
- Such communication enables synchronous measurements among equipment in the vehicles, equipment at the top-of-mast, and radar nodes which are connected to the FRV via fiber



Measurement Synchronization Products

Ettus Octoclock-G reference

- 10 MHz (x8) and PPS (x8)
  - coax connections to masthead
- GPS input from roof-mounted antenna
- ~50 nsec timing synchronization



White Rabbit

- Ethernet-based synchronization: extension of IEEE-1588 (Precision Time Protocol)
- Provides sub-nanosecond timing synchronization and sharing of 10 MHz reference among network nodes
- Requires connectivity using single-mode fiber
- Does not require line-of-sight to GPS satellites (e.g., indoor applications)
- Available products from Seven Solutions

Measurement Synchronization Remarks

Octoclock-G

- 10 MHz outputs provide frequency synchronization among connected instruments (and Tx/Rx channels)
- PPS outputs provide timing synchronization among connected instruments so that all Tx/Rx channels can trigger simultaneously
- GPS-disciplined oscillators provide synchronization from unit-to-unit (such as from FRV to FRV) such that the 10MHz reference and PPS from separate Octoclocks will be synchronous

LO reference sharing

- For some instruments, additional phase coherency is possible by LO reference sharing (NI PXIe 4x4 and 8x8 systems, Ettus X310/TwinRx, Ettus N310)

Distributed measurement software (ND custom SDR application)

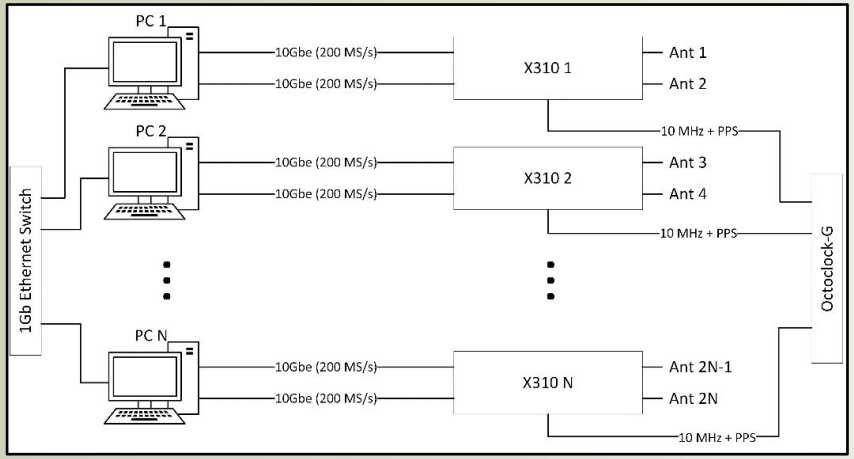
- Multiple software instances can be run simultaneously and linked together over a standard local area network for synchronous operation among all connected devices
- With FRV-to-FRV networking (via virtual tunnel over cellular internet connection or via direct fiber / cable connection), software instances can be linked across multiple computers in both FRVs

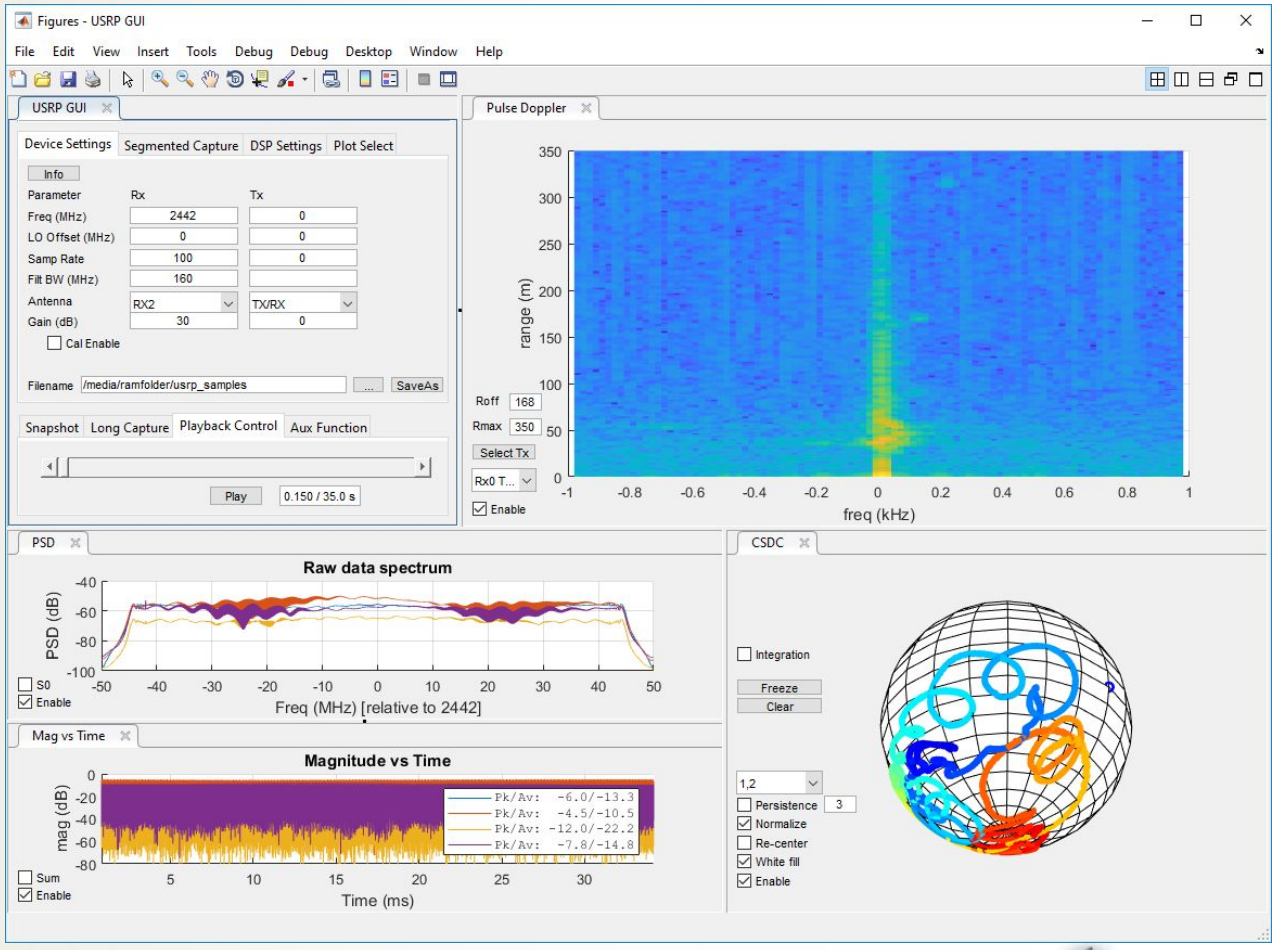
Available Instrumentation

- Dual-polarized antennas
  - Two broadband (0.4-6.0 GHz)
  - Two broadband (6.0-18.0 GHz)
  - Narrowband (0.4, 0.9, 2.4, 5.8 GHz)
- Ettus SDR systems
- Coherent-MIMO systems
  - 8x8 or dual 4x4, to 20 GHz, 200 MHz bandwidth
  - 4x4, to 6 GHz, 1000 MHz bandwidth
  - Custom 16x16 RFSoC-Based systems
- GPS-locked 10 MHz / PPS reference
- Mast-mounted IP camera
- Power amplifiers (0.9, 2.4, 5.8 GHz)
- CP Cases 10U portable 19” racks (4)
- RF-over-fiber link (1km)
- Laboratory equipment
  - Signal generators, spectrum analyzer, oscilloscopes, power sensors

Streaming software

- Custom-developed streaming software split into two programs in a client / server architecture
  - Client: Matlab-based GUI
  - Server: C++ based streaming application
- Supports 3 operational modes:
  - Continuous capture (without processing / display)
  - Repetitive snapshot (pseudo-realtime mode)
  - Playback mode (from previously captured data files)
- Distributed software architecture allows synchronized operation on N workstations to support $2N$ channels streaming at 200 MS/s each





Equipment comparison

Capability	Ettus X310/UBX	Ettus N310	NI C-MIMO PXIe system	NI PXIe system
RF coverage (GHz)	0.1 – 6.0	0.1 - 6.0	0.1 – 18.0	0.1-6.0
Inst bandwidth (MHz)	160 (200 MS/s)	100 (125 MS/s)	160 (200 MS/s)	1000 (1250 MS/s)
Number of channels	2 per device (expandable)	4 per device (expandable)	Up to 8 channels (4 per chassis)	Up to 4
Continuous capture depth	To RAM at 200 MS/s for 75 sec To RAID at 50 MS/s for 83 min	To RAM at 125 MS/s for 60 sec To RAID at 62.5 MS/s for 33 min	To RAID for 30 min	To SSD at 625 MS/s for 7 min
Portability / Installation	Small size/weight along with fiber connectivity allows SDR equipment to be located remotely - Can be installed in custom boxes atop the FRV mast	Small size/weight along with fiber connectivity allows SDR equipment to be located remotely	System components are installed in a 14U portable case which can be secured in FRV equipment bay - Can be used with roof-rail-mounted antennas	System components are installed in a 10U portable case which can be secured in FRV equipment bay
LO sharing	Independent LO per channel, each locked to 10 MHz reference	LO sharing possible 0-4 GHz with externally provided reference	Shared LO among all channels provides superior channel-to-channel phase correlation	Shared LO among all channels provides superior channel-to-channel phase correlation
FPGA	Xilinx Kintex-7 FPGA (XC7K410T)	Xilinx Zynq-7100 SoC with ARM CPU	NI ATCA-3671 incorporating 4 Virtex-7 690T FPGAs	NI ATCA-3671 incorporating 4 Virtex-7 690T FPGAs