Broadening broadband VLBI to also observe GNSS signals

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Overview

- Scientific motivation – an improved geodetic TRF
- Goals and impact
- Two-phase approach
  - Evaluation phase
  - Research and development (R&D) phase
- Preliminary results
- Future work
- Conclusion

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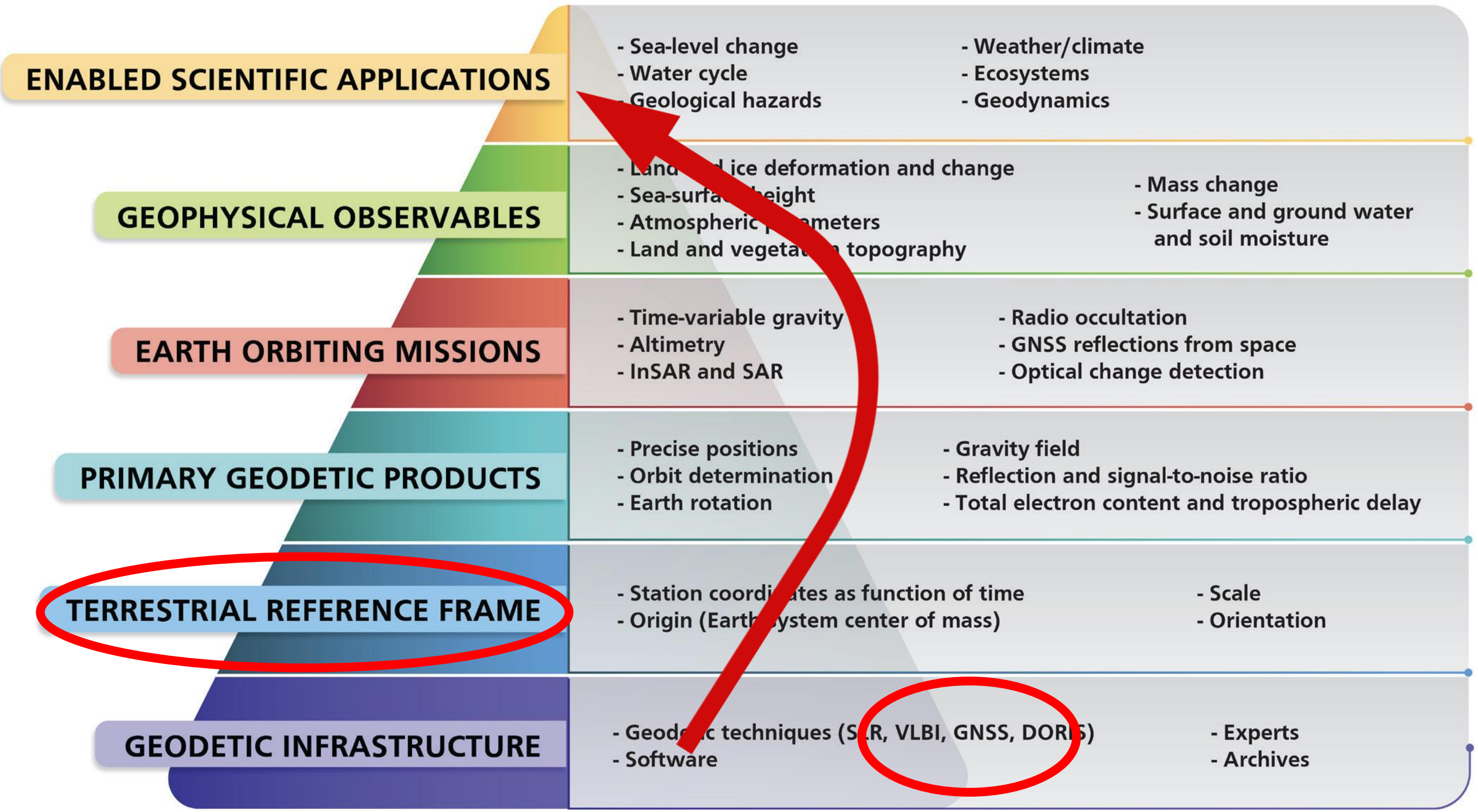
Space Geodesy – Terrestrial Reference Frame (TRF)

- The space geodetic infrastructure (e.g., VLBI and GNSS) is vital to meet pressing scientific and societal needs

- Geodesy realizes a TRF that enables satellite methods, geophysical observations, and key science applications such as sea-level change, weather, and climate



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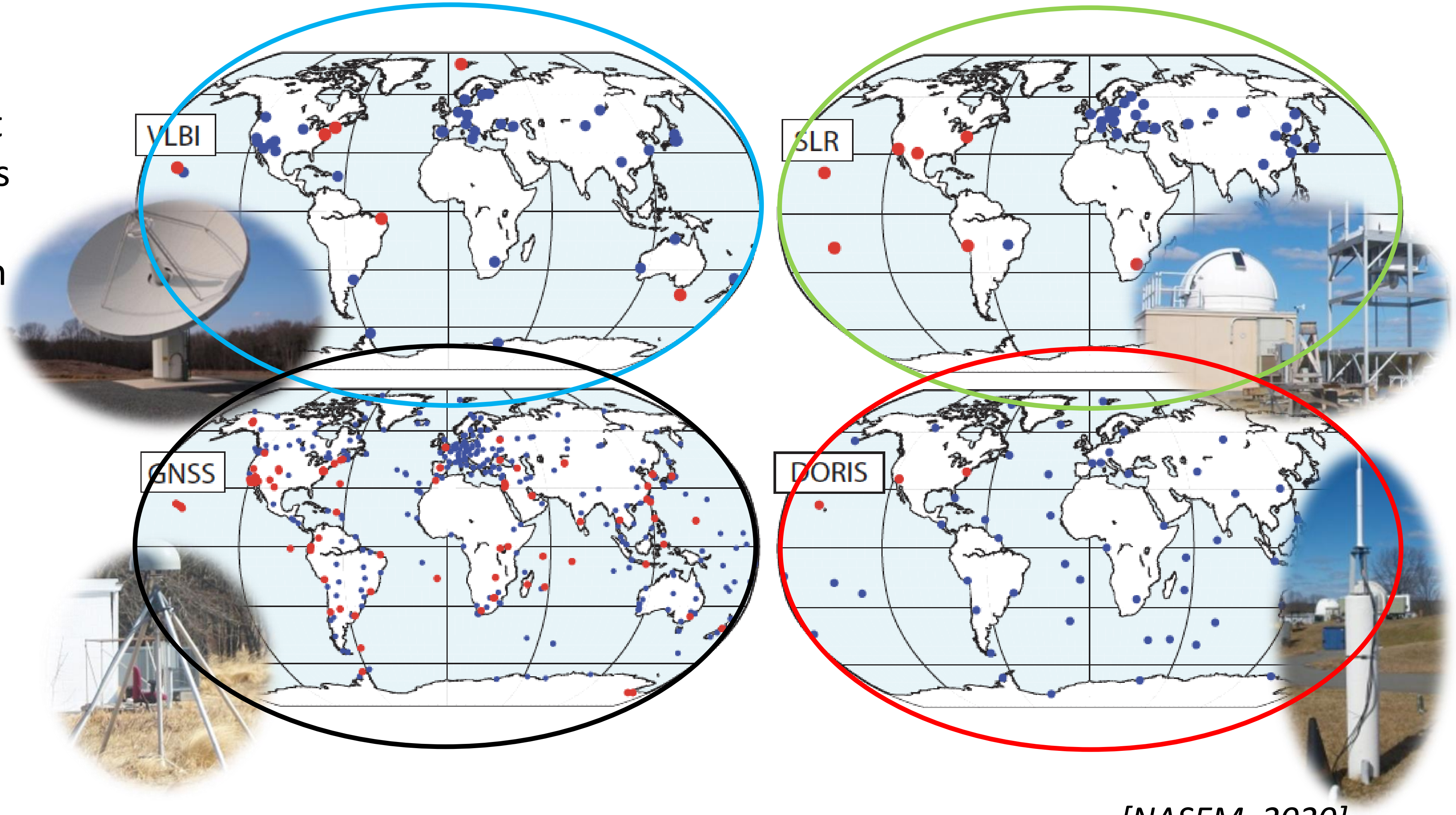
[NASEM, 2020]

Terrestrial Reference Frame (TRF)

- TRF is foundational for virtually all ground- and space-based Earth observation programs
- The positions of objects are determined in relation to an underlying TRF, and the accuracy with which such objects can be georeferenced ultimately depends upon the intrinsic frame accuracy
- Terrestrial (and celestial) reference frames determined by space-geodetic observing systems provide the universal standard against which the Earth's changing shape and its rotation are measured, and represent the tool through which space- and ground-based Earth observations can be connected in space and in time

Space Geodesy Techniques – Independent TRFs

- Each geodetic technique realizes an independent TRF, each having different strengths and weaknesses
- A far more robust TRF can be achieved by merging the individual TRFs (i.e., applying inter-technique vector ties)
- We have devised an approach to tie the VLBI and GNSS TRFs



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Problem – Why tying the TRFs together is important

- Local geodetic ties are a limiting error source in establishing an accurate (1 mm positioning) and stable (0.1 mm/yr) TRF
- What are local geodetic ties?
  - The baseline vectors between antenna reference points at co-located sites necessary to effectively tie the otherwise disconnected reference frames of the individual space geodetic techniques, such as VLBI and GNSS, into a unified TRF
- Unfortunately, the disagreement between local (surveying) ties and geodetic position estimates can be significantly larger (i.e., several mm) than their combined error estimates

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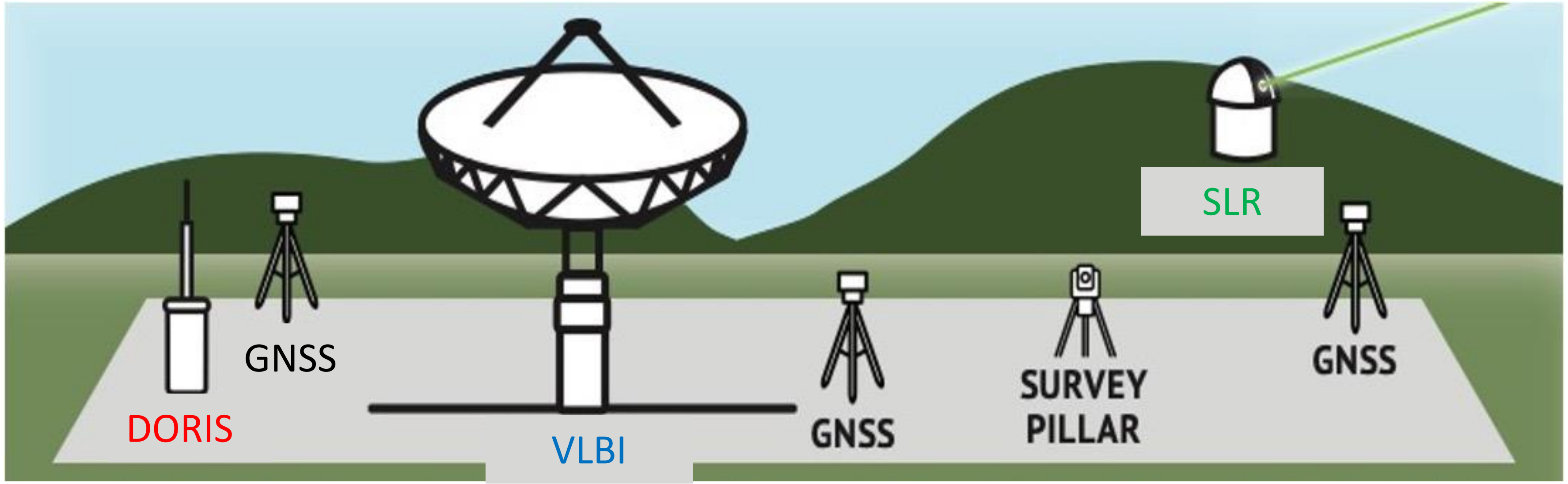
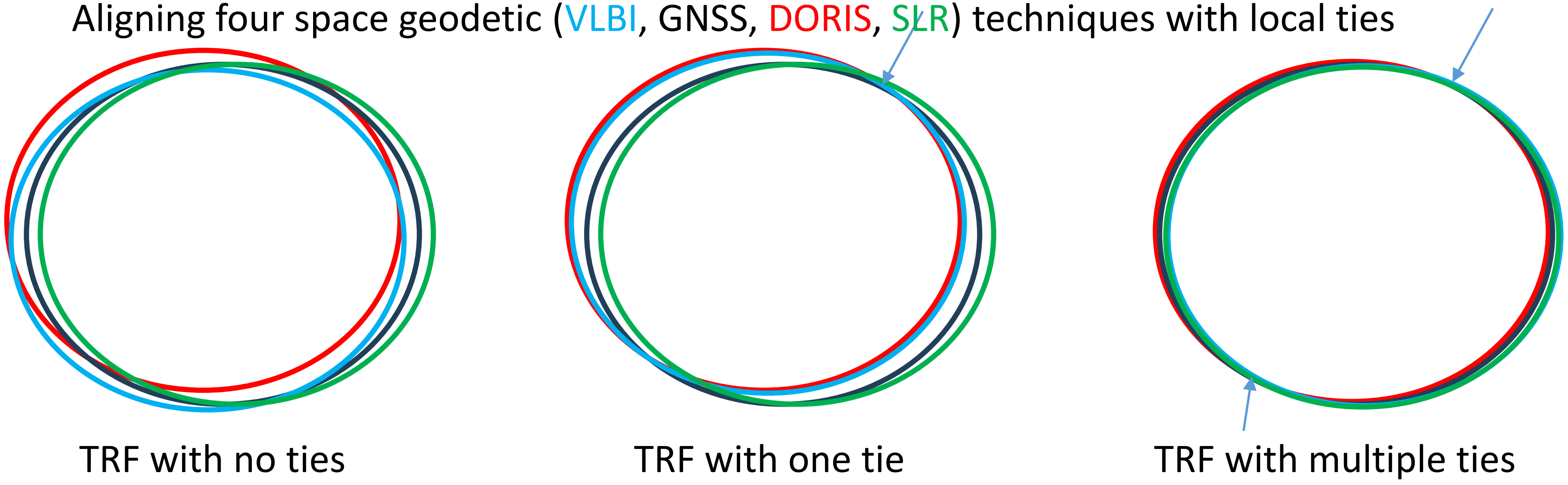
Tying geodetic techniques (hence TRFs) at core sites

- Co-located geodetic techniques at core sites can tie the individual TRFs together as long the vectors between instruments are accurately (<<1 mm) known
- Inter-technique vector ties at core sites nudges the independent TRFs into a single, improved TRF



Aligning four space geodetic (VLBI, GNSS, DORIS, SLR) techniques with local ties



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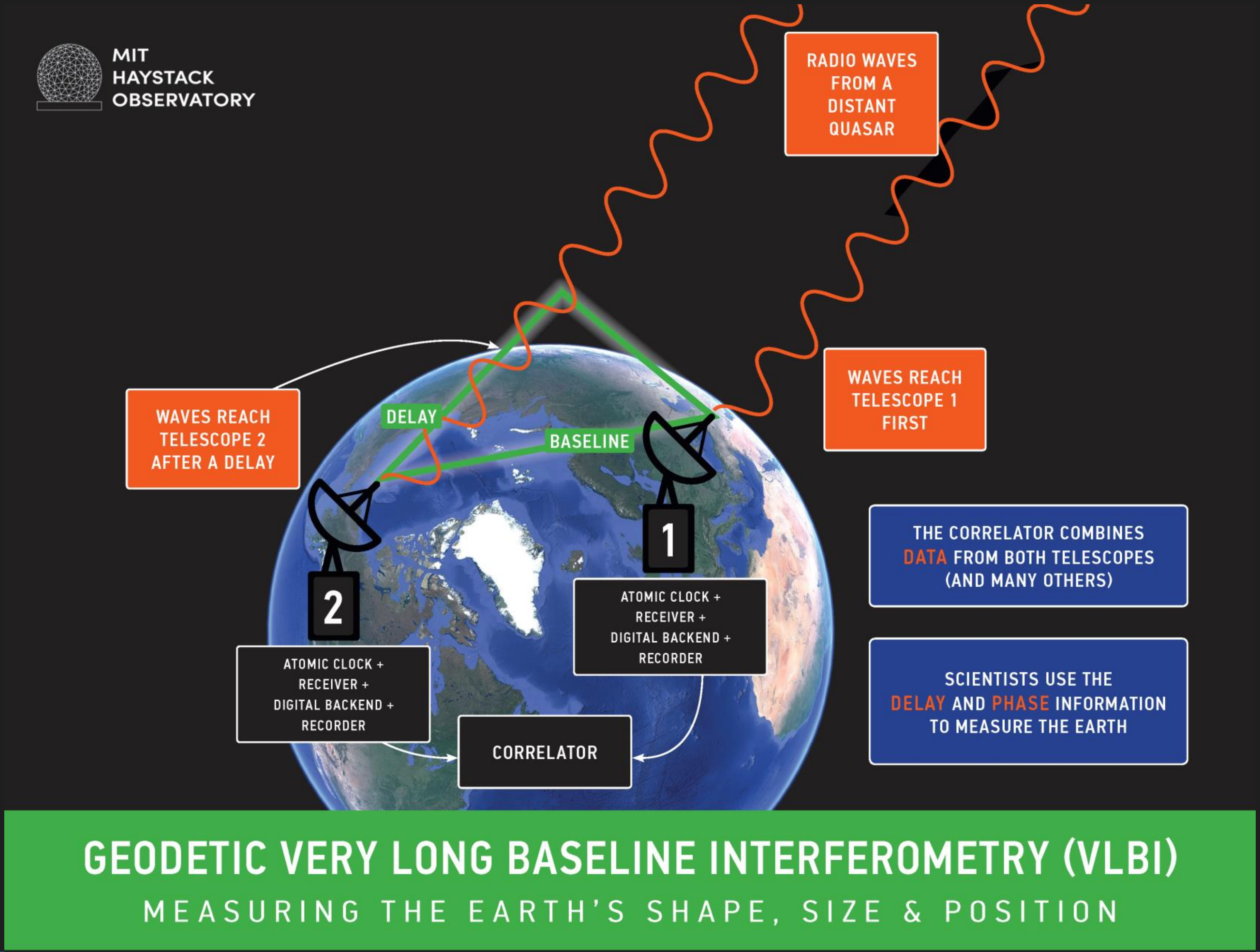
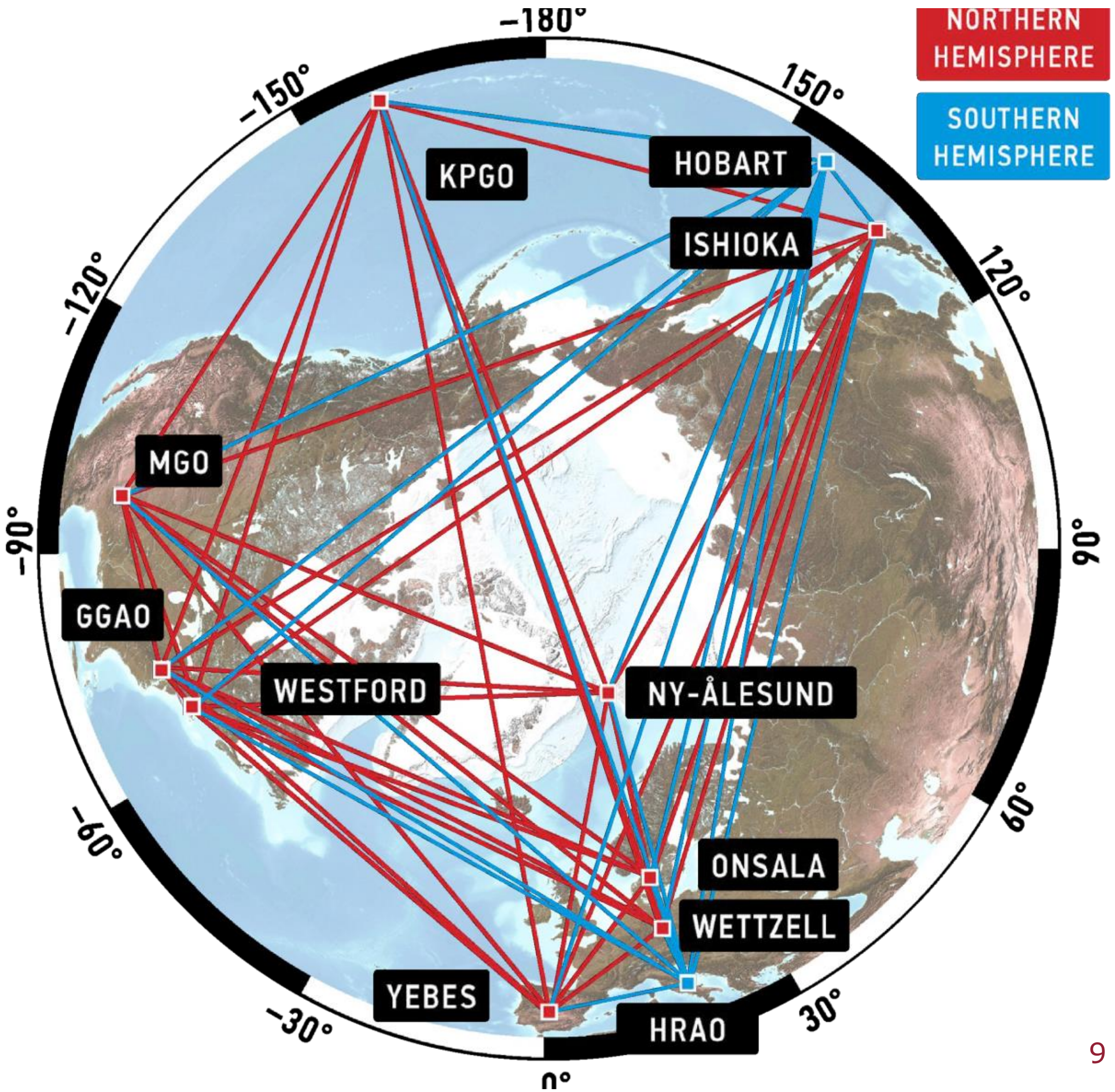
[Modified after Mondal et al., 2024; Hippenstiel, 2024]

Very Long Baseline Interferometry (VLBI)



Next-generation broadband geodetic VLBI (aka VGOS) network

- Existing VGOS capable antennae (black) and resulting northern (red) and southern (blue) hemisphere baselines



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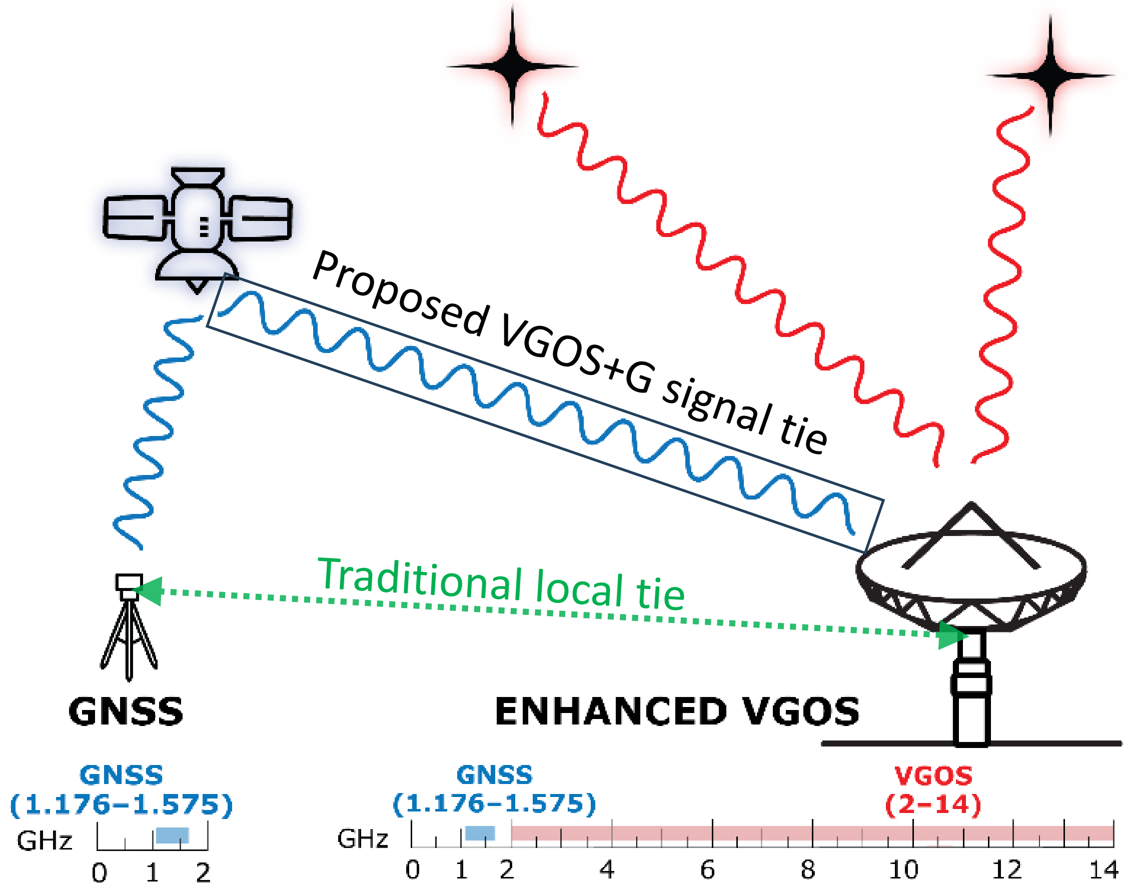
VGOS+G: proposed VGOS plus GNSS tie concept

- Enhance VGOS (2-14 GHz) to also double as a GNSS receiving system (1.1-1.6 GHz) thus fusing the VGOS and GNSS techniques into a single observing instrument
- Construction of such an instrument does effectively tie both geodetic techniques together



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Some VGOS+G facts and features

- Broadens the VGOS low-frequency end from 2 GHz down to 1 GHz
  - Enhances the standard 4-band VGOS system adding a new 5th (G) band
  - Enables the possibility of observing GNSS (i.e., GPS, Glonass, Galileo, and other constellations) signals
  - Uses the very same VGOS antenna to observes both GNSS signals and extragalactic radio sources
  - Integrates the two VLBI and GNSS geodetic techniques into a single instrument hence eliminating the need of local surveying ties

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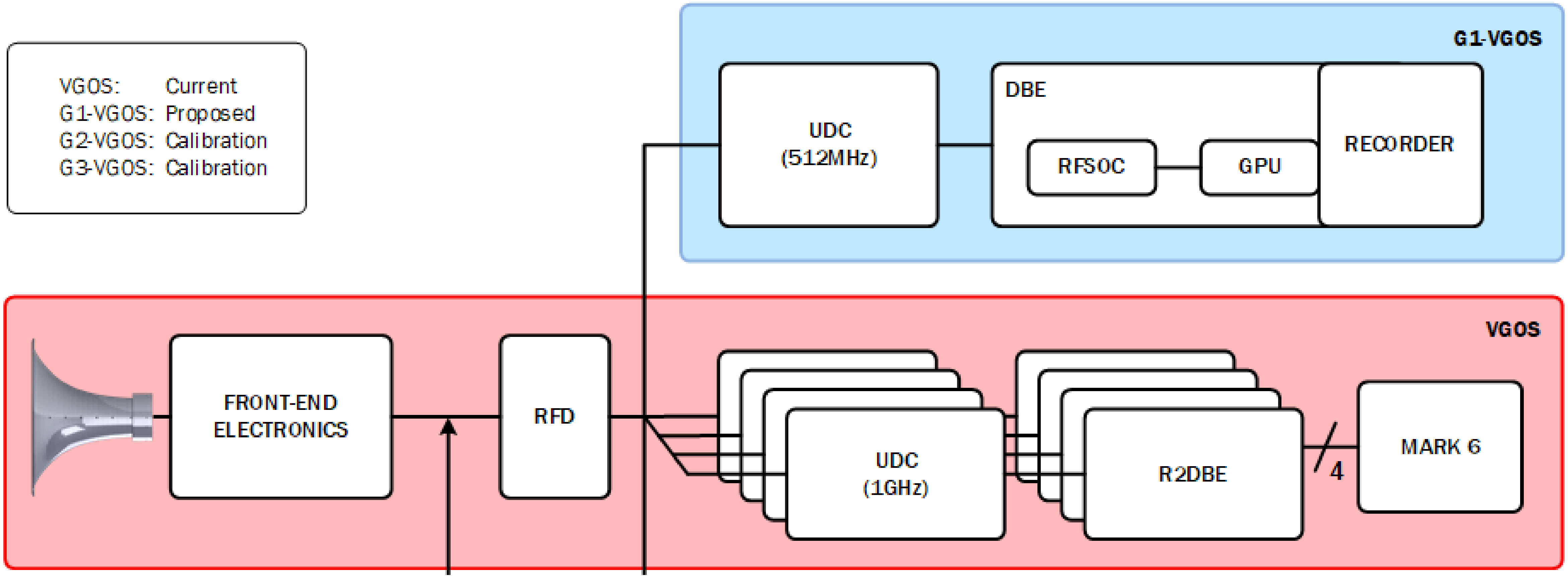
VGOS+G signal chain



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Engineering approach – Two Phases

- Evaluation phase
  - Identify performance challenges of the VGOS signal chain subsystems, from the feed to the DBE, down to 1 GHz.
  - Probe the VGOS feed and antenna at Westford/MIT to assess impacts to the existing systems from RFI, GNSS, or otherwise, and to VGOS operations
- Research and development (R&D) phase
  - Enhance the existing VGOS system by introducing new subsystems to the signal chain such as the fifth-band capability
  - Outline a technology roadmap towards a VGOS+G prototype, and ultimately system and network

Evaluation-phase results

- Key results and recommendations include

1. Westford can ”see” L1 and L2 GPS signals at power levels that are sufficiently low not to risk the integrity of the VGOS signal chain, and without interfering with VGOS operations
2. The Westford high-pass (2.2 GHz) filter can be safely removed to observe GNSS signals; notching the 1.295-GHz radar signal would be required as a mitigation strategy if to keep this permanent.
3. Specific design improvements, such as beyond-decade (20:1) QRFH bandwidth feeds, have been identified that will guide future research directions

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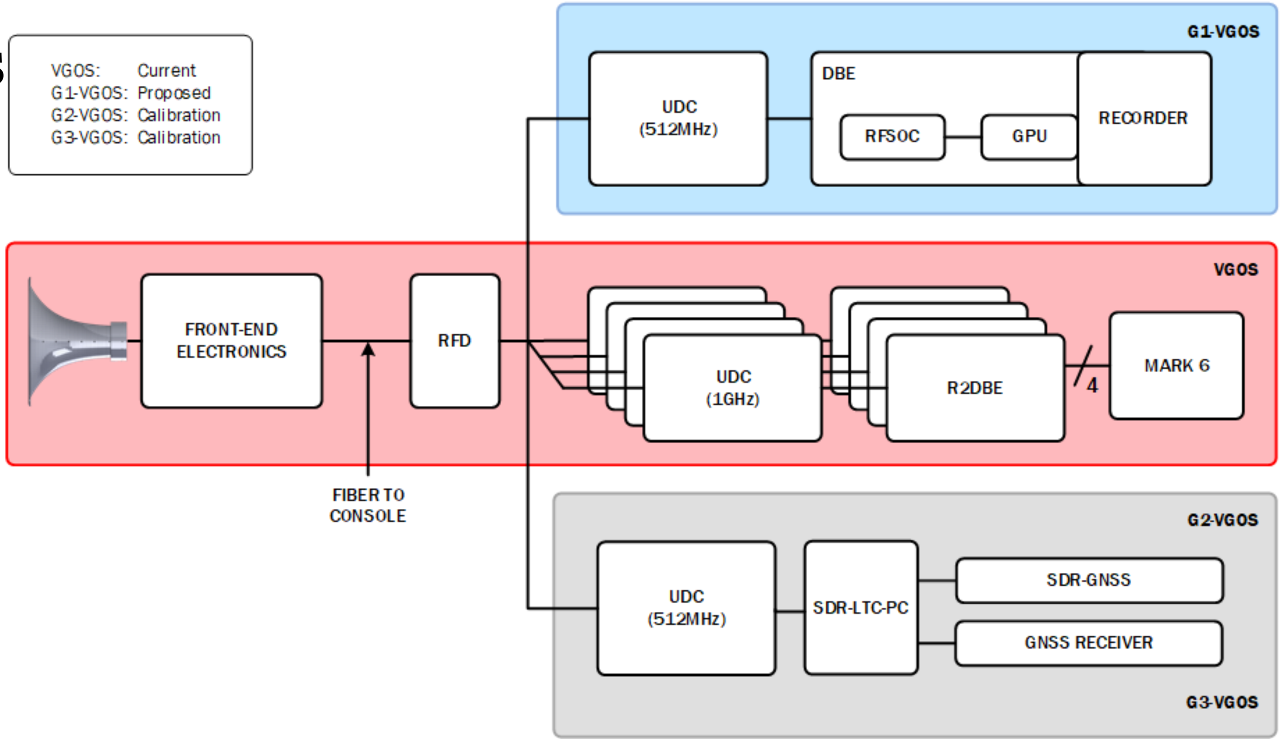
R&D phase

- Validate calibration bands
  - G2- and G3-VGOS signal paths
  - Validation of GNSS software defined radio (SDR) vs COTS GNSS hardware receiver
- Step 1 – against NGS WES2
  - via GNSS antenna
- Step 2 – against each other
  - thru VGOS frontend



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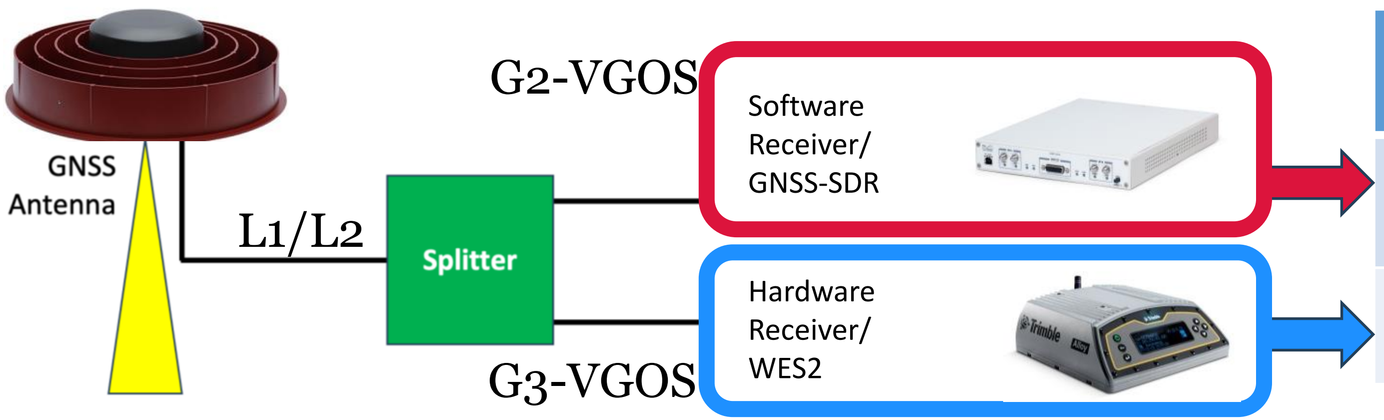
Calibration verification

- G2-VGOS versus G3-VGOS using WES2 (geodetic GNSS site at Westford)
  - Zero-baseline results showed meaningful estimates (further SDR improvements are expected)
  - Goal is to generate high-quality observables that can be processed with geodetic-quality software packages such as *GipsyX* and *GAMIT*

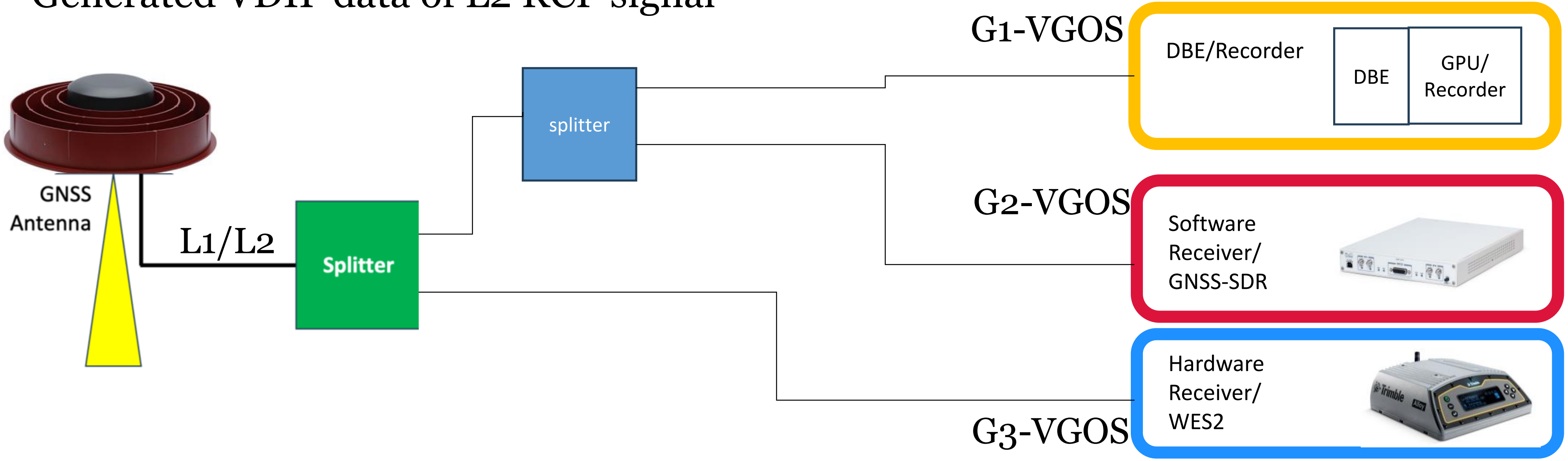


Position error estimates

Station	σX (mm)	σY (mm)	σZ (mm)
GNSS-SDR	40	31	16
WES2	8	8	5

Calibration verification (cont'd)

- G1-VGOS configuration was integrated to calibration chain and recorded L1 and generated VDIF
  - G2- and G3-VGOS output comparison ongoing
  - Generated VDIF data of L2 RCP signal



Radio-Frequency System on a Chip (RFSoC)

- Digitization in the G1-VGOS 5th band is accomplished by an RFSoC
- Digital signal processing configured by an FPGA personality
- The personality initial configuration is to process L1 GNSS signal
  - Generates VLBI digital interchange format (VDIF)
  - 16-bit complex data for 32-MHz channel
  - With G2 / G3 step 1 configuration recorded L1 data from RCP and processed the data with GNSS-SDR
    - To verify signal processing chain
- The final configuration will generate GNSS bands L1 and L2

Next steps

- Insert RFSoC personality into the VGOS signal chain
- Investigate effect of VGOS linear feed vs. circular GNSS signal
- Track GNSS satellite and generate L1 and L2 VDIF observations
- Process GNSS observations with the VLBI correlator and post-processing software (HOPS) at MIT Haystack
- Install a VGOS+G signal chain on a second VGOS antenna for interferometric observations
  - VLBI processing of satellite tracking

Conclusions

- A standard VGOS system can track and observe GNSS satellite signals
  - Though at non-optimal levels
  - RFI mitigation may be required at many locations
- A non-intrusive 5th band addition is possible, though not optimal, for an existing VGOS system
- The calibration path, though a good idea, turned out to be more of a challenge than anticipated
- Circular conversion of linear feed signal is not required for VLBI observing/correlation/post-processing
- A 20:1 broadband feed and matching LNAs would provide an optimal coverage for tying the VLBI and GNSS techniques into a single system

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