# A Cost and Complexity Survey on Emerging Technologies for the VGOS

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**Abstract** Reduction of cost and complexity of VGOS technologies related to the signal chain plays an important role in the proliferation of the new VGOS stations. Focusing on hardware sub-systems ranging from the radio telescope frontend to the VLBI correlator, a survey of current and promising new VGOS-applied technologies is presented along with associated costs and implementation complexity. In the interest of brevity, we present technologies that are currently considered to be the most impactful to the VGOS.

**Keywords** VGOS, system, technology, survey, costs

## 1 Introduction

The cost of the geodetic VLBI technique is undoubtedly a limiting factor in realizing a dense network of VGOS stations. For example, the MIT Haystack Observatory is currently engaged in the development of a signal chain for the new KPGO 12-m antenna currently scheduled for installation in late 2015. The cost and installation of the signal chain for this 12-m antenna, designed and manufactured by Intertronics Solutions Inc., is nearly equivalent to the installed cost of the antenna.

The complexity of a system also plays an important role in the overall cost of a system. In the general case, reduction in the complexity of a system naturally results in a savings in overall system cost; not only in upfront costs but in operations and maintenance costs as well. For this reason, investigations of technologies that reduce the overall complexity of the VGOS signal chain can also significantly drive down the total cost of procuring and operating a VGOS system.

Fortunately for such investigations, technology advancement is a mainstay of our global society and these advancements are to the benefit of the VGOS in the interests of both cost and complexity reduction. In some cases, these technologies are the fruits of academic efforts [1, 2, 3, 4]. In commercial advancements, the economies of scale typically drive down the cost, size, and complexity of key sub-system components [5]. With emphasis on this theme, a survey of these technologies is presented in Section 2 and decomposed into 1) VGOS analog technologies, 2) VGOS mixed-signal technologies, and 3) VGOS digital technologies.

## 2 Emerging VGOS Technologies

Emergence of technologies with application in the VGOS is a very broad subject area spanning across physical hardware, firmware, and computer software, which can find implementations in the analog and/or digital domains. The full scope of this material cannot be covered within the limitations of this publication. Instead, we confine our survey to the presentation of hardware technologies with which Haystack Observatory is familiar and that are considered to be most critical to the VGOS signal chain. Analog, mixed-signal, and digital hardware technologies are presented in the following subsections.
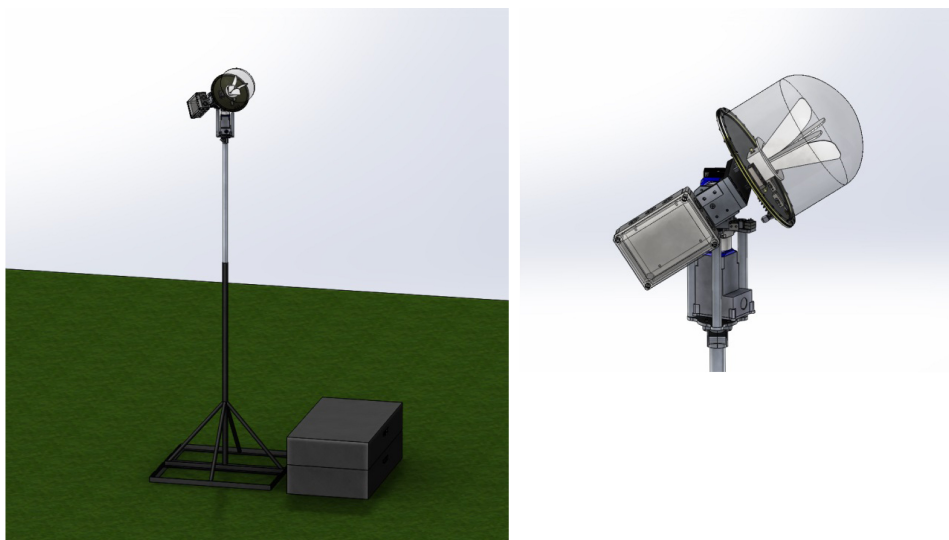
MIT Haystack Observatory

**Fig. 1** 3D model of the proof-of-concept (PoC) RFI monitoring system developed at MIT Haystack Observatory. The spectrum analyzer and data acquisition hardware reside in the black weatherproof enclosure. Replacement of the PoC quad-ridge survey antenna with a reflector-type antenna will improve the sensitivity and directivity of the surveying instrument.

## 2.1 VGOS Analog Technologies

### 2.1.1 RFI Surveying System

Arguably, Radio Frequency Interference (RFI) poses the most significant risk factor to the success of the VGOS. For this reason, it is necessary to conduct wideband RFI surveys as part of a VGOS site selection validation procedure to ensure that such a system can operate below a specified maximum threshold of degradation [6]. It is also desirable to carry out such surveys as part of VGOS standard operating procedures to quantify new sources of RFI and enable schedulers to develop frequency observing plans around these interferers. Portability is a desirable feature of such a surveying system to facilitate ease of deployment at prospective VGOS sites or to simply relocate the surveying antenna at an existing site.

The instrumentation needed to construct such a RFI surveying system consists of four main blocks: (1) 1–18 GHz directional surveying antenna (approximate cost 10,000–15,000 USD), (2) surveying antenna positioner (1,500 USD for the Haystack design), (3) Portable Spectrum Analyzer (20,000 USD), and (4) Data Acquisition and Logging software (Open Source). Figure 1 shows a 3D model rendering of a prototype surveying system developed by MIT Haystack Obser-

vatory to characterize RFI at the KPGO in preparation for the VGOS system installation.

### 2.1.2 Radio Telescope Feeds

The broad instantaneous/continuum frequency coverage specified for VGOS observations requires a radio telescope feed that possesses high aperture efficiency over nearly a decade of bandwidth. Such a feed must also facilitate integration with cryogenically-cooled low noise amplifiers to realize the system temperature specifications that have been set forth for VGOS. These two requirements impose a very challenging design problem to antenna engineers and for this reason selection of such feeds is limited. Figure 2 outlines three feeds that are reported to achieve the performance requirements and capabilities of such a design. To date, only the Eleven and Quadridged Flared Horn (QRFH) antennas have hardware realization and only the QRFH has been implemented at a VGOS station. When used as feeds for the Intertronics 12-m antenna, both antennas will provide 2–14 GHz aperture efficiency performance in excess of 50% [11].

As a two-port single-ended/unbalanced design, we consider the QRFH antenna to be the least complicated feed design. This is significant in that it facilitates
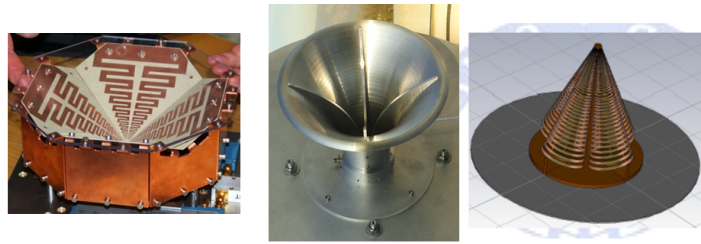
| | Eleven | QRFH | Yebes-Feed |
|---|---|---|---|
| Frequency range (GHz) | 1.2-14 | 2.2-14 | 2.2-14 |
| Polarization | Dual-Linear | Dual-Linear | Dual-Circular |
| Port Configuration | Differential | Single-Ended | |
| LNAs per Polarization | 4 | 1 | 1 |
| LNAs per Feed | 8 | 2 | 4 |
| Calibration Signal Injection | Radiated or post-LNA | Radiated, pre-LNA, or post-LNA | - |
| Aperture Efficiency | > 50% | | 65% - 13.2m Telescope |
| Size | Diameter 210mm height 65 mm | diameter 160mm height 150mm | height 169 mm |
| Cost (USD) | Contact Omnisys | 15K | TBD |

**Fig. 2** Performance and attribute comparison of the Eleven, QRFH, and Yebes radio telescope feeds.

immediate implementation as a radio telescope feed, since single-ended VGOS LNAs are readily available [1] while comparable differential LNAs are not. For this reason, the implementation cost of the QRFH is likely to be the least expensive of the designs considered in Figure 2.

### 2.1.3 VGOS Calibration Subsystem

The VGOS calibration subsystem plays a crucial role in mitigating instrumental biases in the signal chain, particularly those correlated with antenna pointing. If left uncalibrated, these instrumental fluctuations can degrade the accuracy of the observations and lead to systematic position errors in the geodetic solutions. MIT Haystack Observatory has designed and fabricated a 2–14 GHz calibration generator (Figure 3) that provides both amplitude and phase calibration signals, each of which possesses independent level control. Currently, this design will only support phase calibration pulses at a 5-MHz repetition rate.

This calibration signal generator also interfaces with a reference cable delay measurement system. Such a system has been developed at Haystack Observatory in response to a discovery that broadband

observations were suffering from antenna-pointing-correlated reference cable delays at Westford and GGAO stations. A block diagram of this measurement system, that has demonstrated sub-picosecond scale accuracy, is shown in Figure 4. The overall cost of the VGOS calibration signal generator is approximately 30,000 USD; the cost of the cable measurement system is currently being evaluated. Designs for both components will be made available through the MIT technology licensing office.

## 2.2 VGOS Mixed Signal Technologies

### 2.2.1 Modular Monitor/Control Instrumentation

The VGOS signal chain is comprised of a variety of subsystems ranging from the receiver frontend on the telescope to the backend residing in the station operations center. Associated with these subsystems are a variety of monitor and control points that must be accessible through station infrastructure—the station's so-called monitor and control infrastructure (MCI). Examples of these monitor/control points include control of the receiver calibration noise diode, measurements
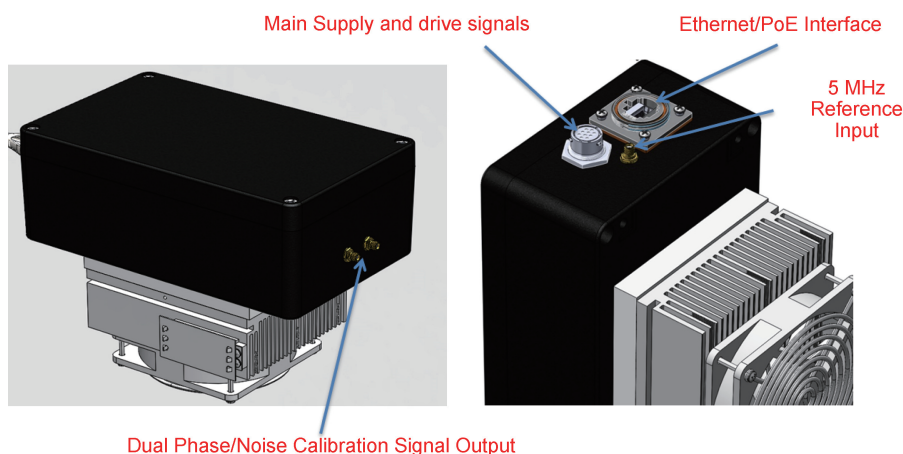
Main Supply and drive signals          Ethernet/PoE Interface

5 MHz
Reference
Input

Dual Phase/Noise Calibration Signal Output

**Fig. 3** 3D model of the VGOS calibration signal generator developed by MIT Haystack Observatory.
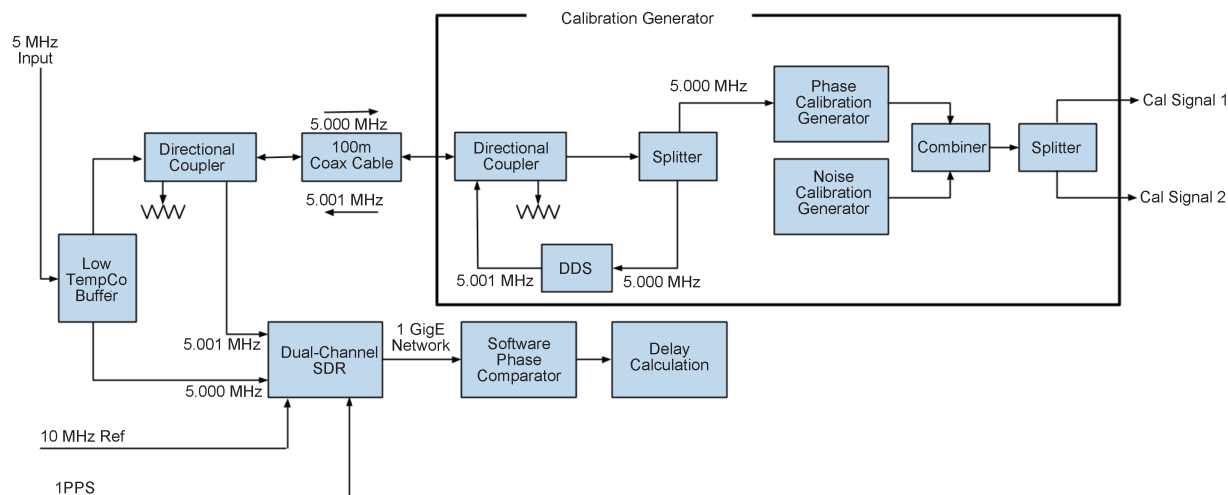
**Fig. 4** Block diagram of the reference cable delay measurement system as integrated with the VGOS calibration signal generator. The instrumentation incorporated to realize this system has demonstrated sub-picosecond scale accuracy.

of ambient temperature/pressure/humidity, and control of signal level attenuators. If not carefully planned out, MCI can become a complex implementation in its own right when considering signal integrity, power supply distribution, and volume/space requirements. To minimize the need for station developers to address such considerations, MIT Haystack Observatory has developed the VLBI Data AcQuistion (VDAQ) module which is an open source hardware development expected to cost 2,000–3,000 USD and the design information will be made available through the MIT technology licensing office.

As a modular instrument, the VDAQ makes dual use of Ethernet infrastructure. The Ethernet backbone provides both a communications and electrical power interface to the module. This feature of the VDAQ and its small form factor (13 cm×10 cm×2.5 cm, see Figure 5) allow it to be deployed to space-limited locations where MCI is needed. This modular concept also serves to minimize issues related to signal integrity since sensors and signal monitors can be placed in close proximity to the module, which can also serve as a distributed power supply. The following provides a breakdown of the interfaces that the VDAQ module will support:
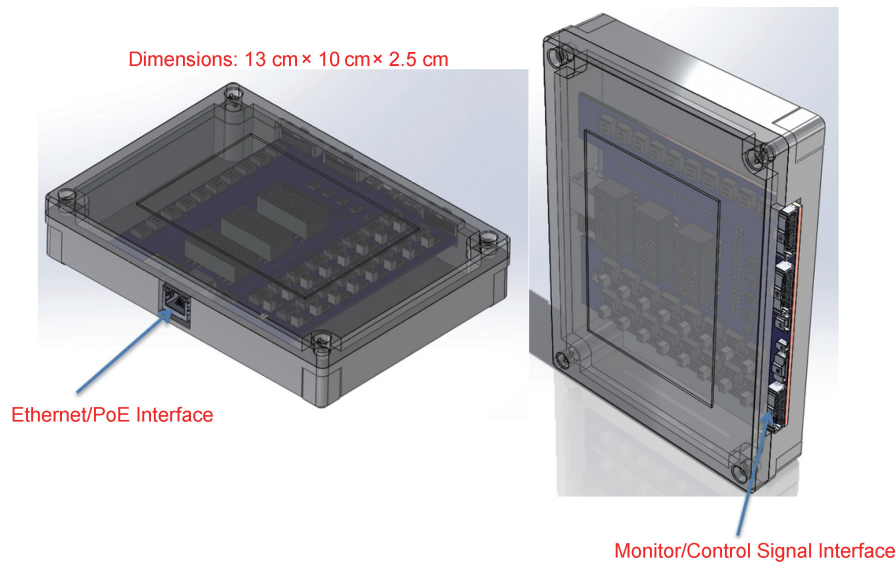
Dimensions: 13 cm × 10 cm × 2.5 cm

Ethernet/PoE Interface

Monitor/Control Signal Interface

**Fig. 5** Notional 3D model of the VLBI Data Acquisition (VDAQ) module.

- Digital Communications

  – RS232
  – $I^2C$
  – SPI
  – Ethernet

- Isolated DC Power Sources
- 16 Analog Monitors

  – Single-ended or Differential
  – Isolated or Non-Isolated
  – Configurable signal conditioning

- 40 Digital Monitors or Controls

  – Ten Isolated Monitors
  – Ten Isolated Controls
  – 20 Non-isolated Monitors and/or Controls

### 2.2.2  High Speed Samplers

In some sense, an analog-to-digital converter serves as the frontend to the VGOS signal chain backend. In order to support the 1-GHz IF band VGOS specification with quantizers possessing sufficient bit depth to accommodate RFI, high speed samplers, by current standards, are necessary to meet this specification [7]. Note that in this context, speed refers to data rate and not

sampling rate; the latter is a component of the former. The Collaboration for Astronomy Signal Processing and Electronics Research (CASPER) has realized two such samplers of note to this end.

The first sampler, model ADC1-3000-8 [8], will clock at sample rates up to 3 GSps with an eight-bit quantizer and supports digitization of a single IF. The ADC1-3000-8 sampler demultiplexes the eight output data streams from the 3-GSps digitizer into 32 data streams at 375 MHz on both edges of the 375-MHz clock waveform (i.e., double data rate – DDR). This demultiplex operation provides relief on the clocking speed at which the FPGA data processor must operate, which is significantly limited relative to that of the digitizer. This sampler can be purchased from DIGICOM Electronics, Inc. at a cost of 2,500 USD.

The second sampler, model ADC1-5000-8 [9], will clock at an aggregate sample rate up to 5 GSps through the use of two digitizing cores. This sampler can be purchased in two configurations: (1) nondemux and (2) demux. The demux mode allows the full bit depth of the samples to be captured at a slower rate relative to the nondemux configuration which provides relief on the speed at which the FPGA data processor must be clocked. In both configurations, the sampler can be setup for interleaved operation (5 GSps digitization of a single IF) or dual IF operation (2.5 GSps digitization of two IFs). In either operating mode, the aggregate data

rate remains the same. However, as a VGOS high speed sampler, the dual IF operating mode is far more attractive, since this mode will support digitization of two VGOS IF bands, whereas the ADC1-3000-8 will only support digitization of a single IF band. This sampler can also be purchased from DIGICOM Electronics Inc. for 1150 USD. This represents a savings of more than a factor of four in terms of Dollars per IF band relative to the ADC-3000-8.

## 2.3 Digital Technologies

### 2.3.1 FPGA Processing

The CASPER has also developed the next (2nd) generation of its Reconfigurable Open Architecture Computing Hardware (ROACH2) board [3] that is shown in Figure 6. This hardware integrates an FPGA processor and an integrated PPC onto one consolidated processing unit. The FPGA performs the processing-intensive digital operations, while the PPC serves as a communications and configuration interface into the FPGA. The ROACH2 FPGA is a Xilinx Virtex6 XC6VSX475T which is reported to support clock rates up to 625 MHz. At double data rate speed, this FPGA can support data transmission on a single physical transmission line (i.e., signal lane) up to 1.25 Gbps. Given that the ROACH2 possesses dual 40 lane signal lanes into the FPGA through its ZDOK interfaces, the ROACH2 can theoretically support a total aggregate data rate of $2 \times 40 \times 1.25 = 100$ Gbps. This represents a 10% improvement in speed relative to the Virtex5 XC5VSX95T FPGA which is integrated into the ROACH1 [3]. The significant gain in the Virtex6 over the Virtex5 are the gains in computing resources (e.g., 2,014 DSP slices V6 vs. 640 DSP slices V5) that facilitate more parallelized operations (e.g., 64 vs. 16 channel polyphase filter bank). The ROACH2 hardware can be purchased from DIGICOM Electronics, Inc. and the cost as of the submission date of this document is 12,000 USD.

For VGOS, the role of input data rate to the digital backend processor is twofold. Firstly, increased data rate facilitates consolidation of digital processing hardware. The more samplers that can be accommodated by a single digital processing hardware unit, the less complex the overall station hardware becomes. Secondly,
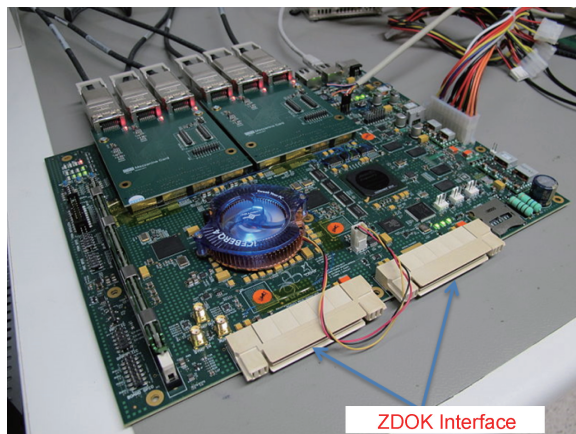


**Fig. 6** Photo image of the Casper ROACH2 computing hardware circuit board.

for a given frequency IF sampling rate (VGOS standard IF bandwidth requires a rate of 2 GSps), increased data rate translates into allowance of digitizers possessing more dynamic range (i.e., more digitization states). This, in turn, provides more immunity to RFI and improves the saturation margin of the overall signal chain.

### 2.3.2 Digital Recording

The Mark 6 16-Gbps data recorder [4] was developed at MIT Haystack Observatory through a commercial partnership with Conduant Corporation. The Mark 6 recorder was developed as an open-source software development and makes use of generic, high-performance commercial-off-the-shelf hardware. This recorder is available in 8 or 16 Gbps models. The latter requires a diskpack expansion chassis to circumvent the limitations on hard disk write speeds. With solid-state disk drives (SSDs), the recorder is expected to achieve rates up to 64 Gbps.

The cost of the 16-Gbps model of the Mark 6 is 14,000 USD while that of the 8-Gbps model is 11,000 USD. The diskpack carrier is identical for both models, costs 500 USD, and can be populated with up to eight recommended COTS SATA hard disks. As of the date of this publication (2014 Apr 30), a suitable 2 TB Seagate Barracuda hard disk can be purchased for 85 USD so that a 16-TB Mark 6 diskpack can be constructed for 1,180 USD including the cost of the diskpack carrier. The Mark 6 8/16 Gbps models require

a total of two and four diskpacks, respectively, to sustain the maximum data rate. Therefore, the total minimum cost to operate the 8 and 16 Gbps models with 16-TB diskpacks is 13,400 USD and 18,700 USD, respectively.

Two Mark 6 recorders will satisfy the VGOS requirement on data recording rates (32 Gbps [10]) and SSDs promise to condense the requisite hardware to a single recorder. This feature of the Mark 6 significantly reduces the complexity of the VGOS signal chain. As a matter of example, a single Mark 6 recorder can sustain data storage at a rate equivalent to the aggregate data rate of four Mark 5C recorders, eight Mark 5B+ recorders, or 16 Mark 5B recorders. The reduction in complexity represents a significant savings in upfront procurement costs for the VGOS signal chain. Furthermore, the Mark 6 is capable of supporting diskpacks with much denser data storage than was possible by its predecessors. This fact also represents a significant cost savings in operations and maintenance, since more data can be stored onto fewer diskpacks, which translates to fewer diskpack procurements and reduced shipping costs.

## 3 Summary

Start-up procurement costs for a VGOS station are significant, as are the costs to operate and maintain these stations. For these reasons, administrators should be cognizant of the costs associated with emerging VGOS technologies and system developers with the associated complexities for operations and maintainability. To limit the scope of this survey, we presented only those technologies that are currently considered to be most impactful to the VGOS. The following outlines procurement costs for the technologies described in Section 2:

- RFI Monitoring System: ~40,000 USD
- QRFH: 15,000 USD
- Calibration Signal Generator: ~30,000 USD
- VDAQ: ~2,000–3,000 USD
- High Speed Samplers

  – ADC1-3000-8: 2,500 USD
  – ADC1-5000-8: 1,150 USD

- ROACH2: 12,000 USD

- Mark 6

  – 16-Gbps Model: 14,000 USD
  – 8-Gbps Model: 11,000 USD
  – Empty Diskpack: 500 USD

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