**Raytheon**
**BBN Technologies**

**BBN Technologies**
10 Moulton Street
Cambridge, MA 02138

10 March 2016

Office of Naval Research
875 North Randolph Street, Suite 1179
Arlington, VA 22203-1995

Delivered via Email to:
richard.t.willis@navy.mil
reports@library.nrl.navy.mil
tr@dtic.mil
ryan.bell2.ctr@navy.mil

| | |
|---|---|
| **Contract Number:** | N00014-14-C-0002 |
| **Proposal Number:** | P13003-BBN |
| **Contractor Name and PI:** | Raytheon BBN Technologies; Dr. Jonathan Habif |
| **Contractor Address:** | 10 Moulton Street, Cambridge, MA 02138 |
| **Title of the Project:** | Seaworthy Quantum Key Distribution Design and Validation (SEAKEY) |
| **Contract Period of Performance (Base + Option):** | 7 February 2014 – 9 September 2016 |
| **Total Contract Amount (Base + Option):** | \$475,359 (Base) + \$199,252 (Option) |
| **Amount of Incremental Funds (Base + Option):** | \$475,359 (Base) + \$115,189 (Option) |
| **Total Amount Expended (thru 4 March February – Base + Option):** | \$456,461 (Base) + \$40,432 (Option) |

Attention: Dr. Richard Willis
Subject: Quarterly Progress Report
Reference: Exhibit A, CDRLs

In accordance with the reference requirement of the subject contract, Raytheon BBN Technologies (BBN) hereby submits its Quarterly Progress Report. This cover sheet and enclosure have been distributed in accordance with the contract requirements.

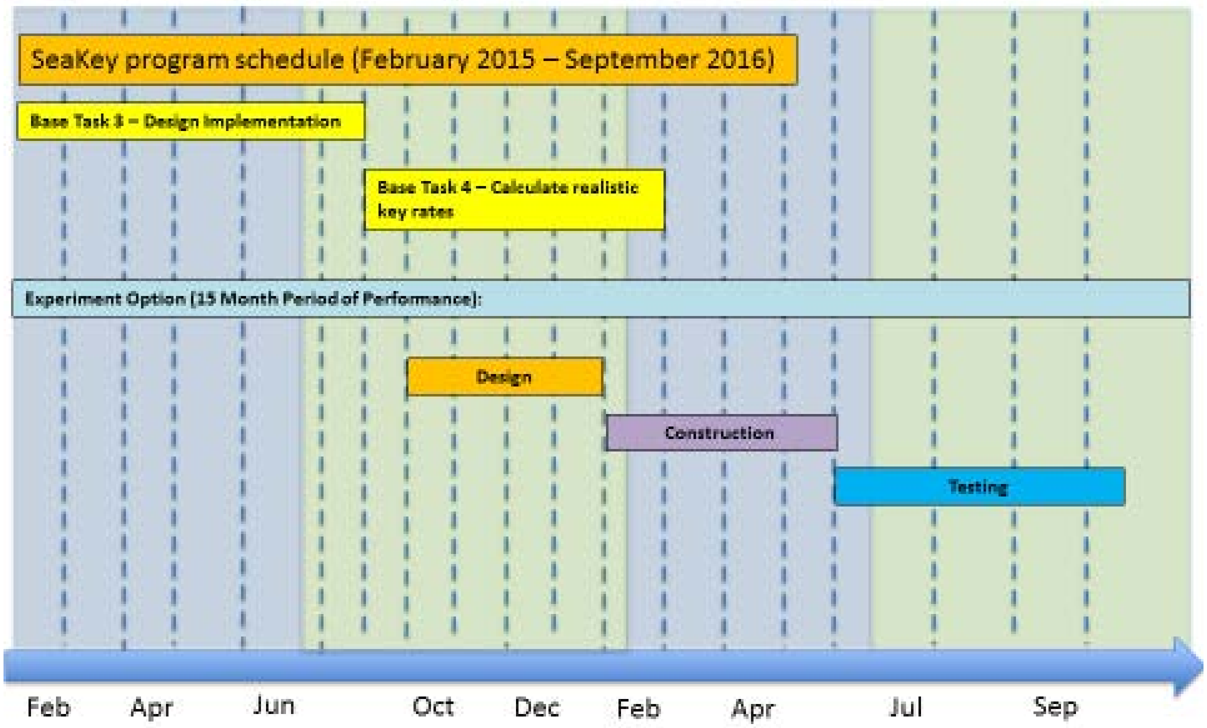
Please do not hesitate to contact Dr. Habif at 617.873.5890 (email: jhabif@bbn.com) should you wish to discuss any technical matter related to this report, or contact the undersigned, Ms. Kathryn Carson at 617.873.8144 (email: kcarson@bbn.com) if you would like to discuss this letter or have any other questions.

Sincerely,
Raytheon BBN Technologies

Kathryn Carson
Program Manager
Quantum Information Processing

## Section A. Project Schedule

The Year 2 timeline below identifies the high level SeaKey tasks and approximate durations.




## Section B. Technical Progress

### *SUMMARY*

In this report we summarize the technical progress accomplished during the fourth quarter of the second year of the SeaKey program. In this quarter we started work on our experimental option task and that progress will be reported here.

This quarter we have continued work calculating the key rates achievable parametrically with receiver performance. In addition, we describe the initial designs and construction of the CV-QKD transmitter and receiver we are planning to build, and provide an update on the construction of those sub-systems.

***TECHNICAL RESULTS***

In our program review presentation, we emphasized the critical role that noise plays in determining the range of CV QKD systems.  In Figure 1 we show the theoretical rate (in bits/s) vs. range (in km) of a CV QKD implemented using a homodyne detector for various values of generalized common-mode rejection ratio (CMRR).  Clearly, the electronic and environmental noise as well as imbalance in the homodyne detection can cause severe (if not fatal) degradation in performance of CV QKD systems. In this quarter we focused on identifying means to mitigate this degradation.

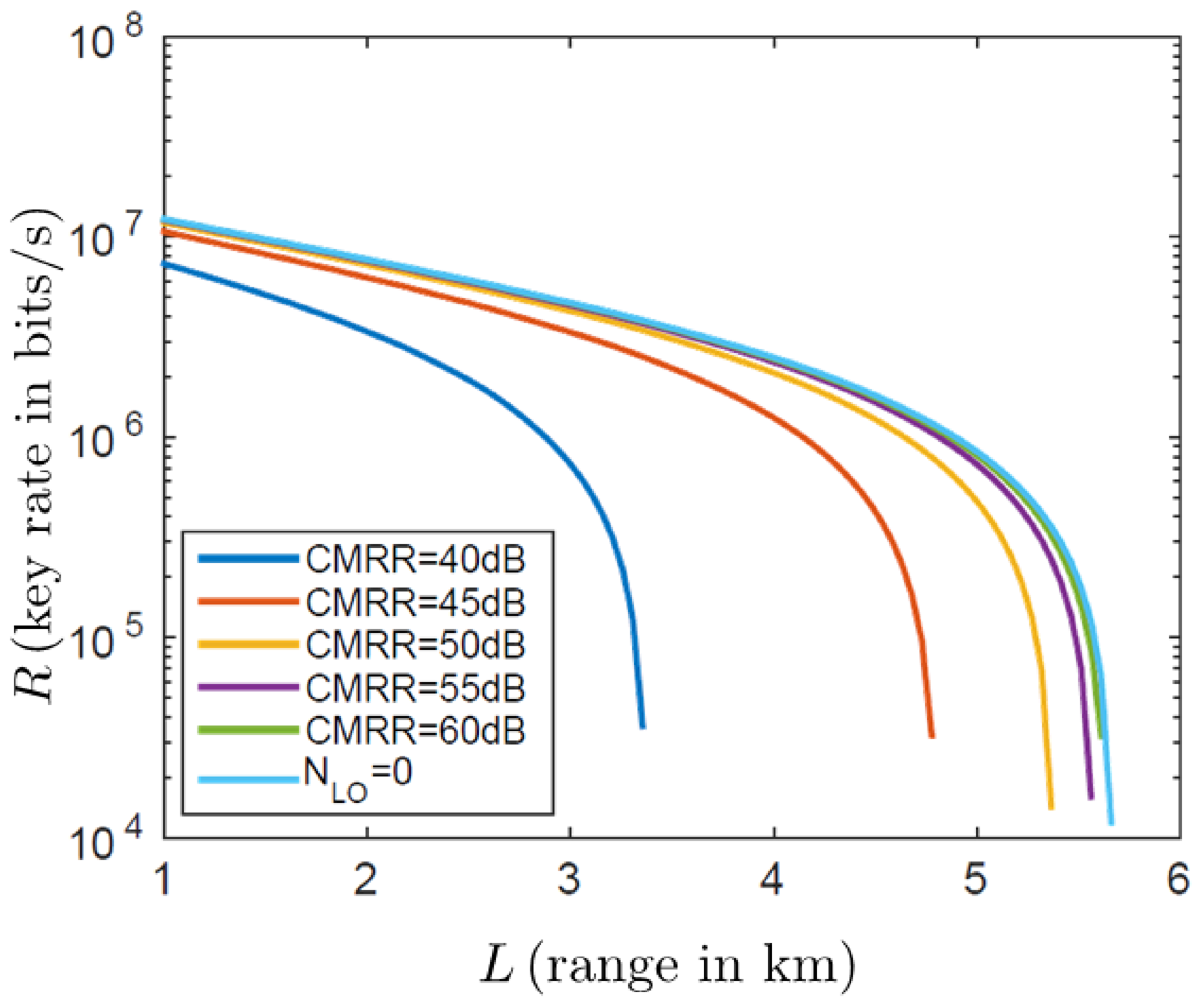



Figure 1. Rate vs. distance performance of CV QKD system employing a homodyne detector for various values of generalized common-mode rejection ratio (CMRR), which accounts for the imbalance in the optical arms and the asymmetry in the differential amplifier of the detector. Detector is operating at wavelength $\lambda = 1.55\mu$m with electronic bandwidth $B = 100$MHz, the contribution of the electronic (internal) and environmental (external) noises of $\delta_e = 0.056$ and $\delta_A = 0.045$ photons per pulse, respectively.  The apertures for both receiver and transmitter are circular with equal radii $r_R = r_T = 0.1$m.

The efficiency of the detector $\eta_d = 0.98$ while that of the error correction coding is $\beta = 0.898$. The power of the local oscillator (LO) is $P_{LO} = 20$mW while its relative fluctuation is $\Delta P_{LO} = 0.1\%$RMS. We calculate the contribution $N_{LO}$ of LO fluctuations in the local oscillator to the noise for each CMRR using equation (11) in Che *et al.*, New J. Physics **13** (2011) 013003. We also plot the idealized case $N_{LO} = 0$ when either the detector is perfectly balanced (CMRR= ∞) or the LO is perfectly stable ($\Delta P_{LO} = 0$). We optimize the repletion rate and transmitter power.

Our ideas can be summarized as follows:

1. Measuring LO concurrently to reduce the impact of deleterious fluctuations: we are investigating a novel approach to homodyne detection where a portion of LO is split off and directed towards a third photodetector, which measures its intensity. This measurement, which would capture the LO fluctuations) would then be used to reduce the noise of the homodyne detector. This is effectively an electronic active control system which could increase the CMRR beyond what could be achieved by other means (such as mechanical active control systems for the stability of the detector arms).
2. Taking advantage of finite constellation modulation in our CV QKD approach, we could potentially allow the use of lower-resolution A/D converters, and result in reduction of electronic noise (as well as SWaP).

### Design for a Free-Space CV – QKD System

We continue to make progress in the construction of the experimental setup for the measurement of atmospheric transmission of phase-encoded coherent states. Currently, we are focusing on the construction of the homodyne receiver. Figure 2

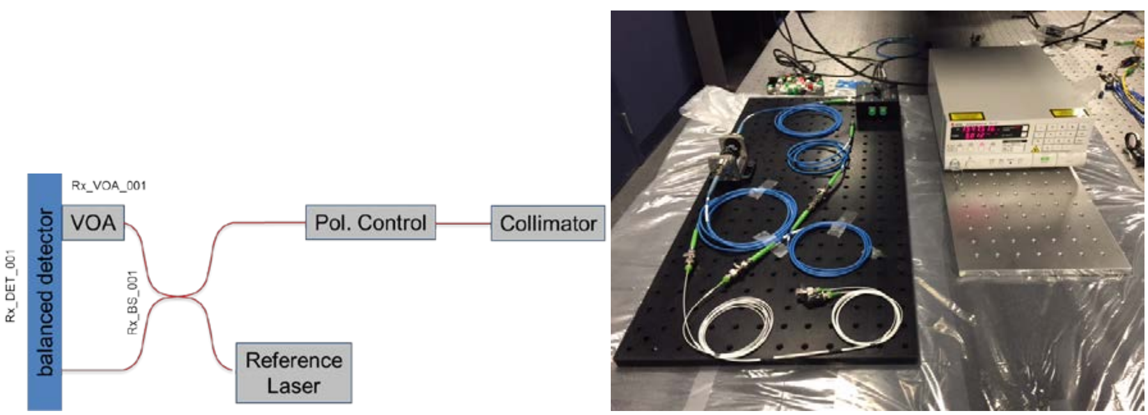



Figure 2 Spiral 2 receiver design, following the self-referenced CVQKD proposal.

shows the design for the homodyne receiver, along with the current fiber-based laboratory implementation of the receiver. The components were purchased from ThorLabs Inc., except for the polarization-maintaining 50:50 beamsplitter that performs mode-mixing in the receiver, which was purchased from Oz Optics. The laser is a Santec tunable laser generating approximately 5 mW of optical power at 1550 nm.

A key component in the system is the variable optical attenuator (VOA) required to balance the optical power in the output arms of the beamsplitter, compensating for non-uniformity of the beamsplitting ratio. We attempted several designs for this VOA, but ran into problems achieving sufficient simultaneous stability and tenability. At this time, we have arrived at a solution which involves rotating a half-waveplate inside a free-space precision rotation mount, centered between left-handed and right-handed beam displacer modules. This allows for tunable attenuation, irrespective of the input polarization of the light. While, thus far, this has proven to be a very stable solution, the tuning is manual and very sensitive. We are currently examining replacing the precision rotation mount with one that has a micrometer integrated for fine adjustment of overall loss.

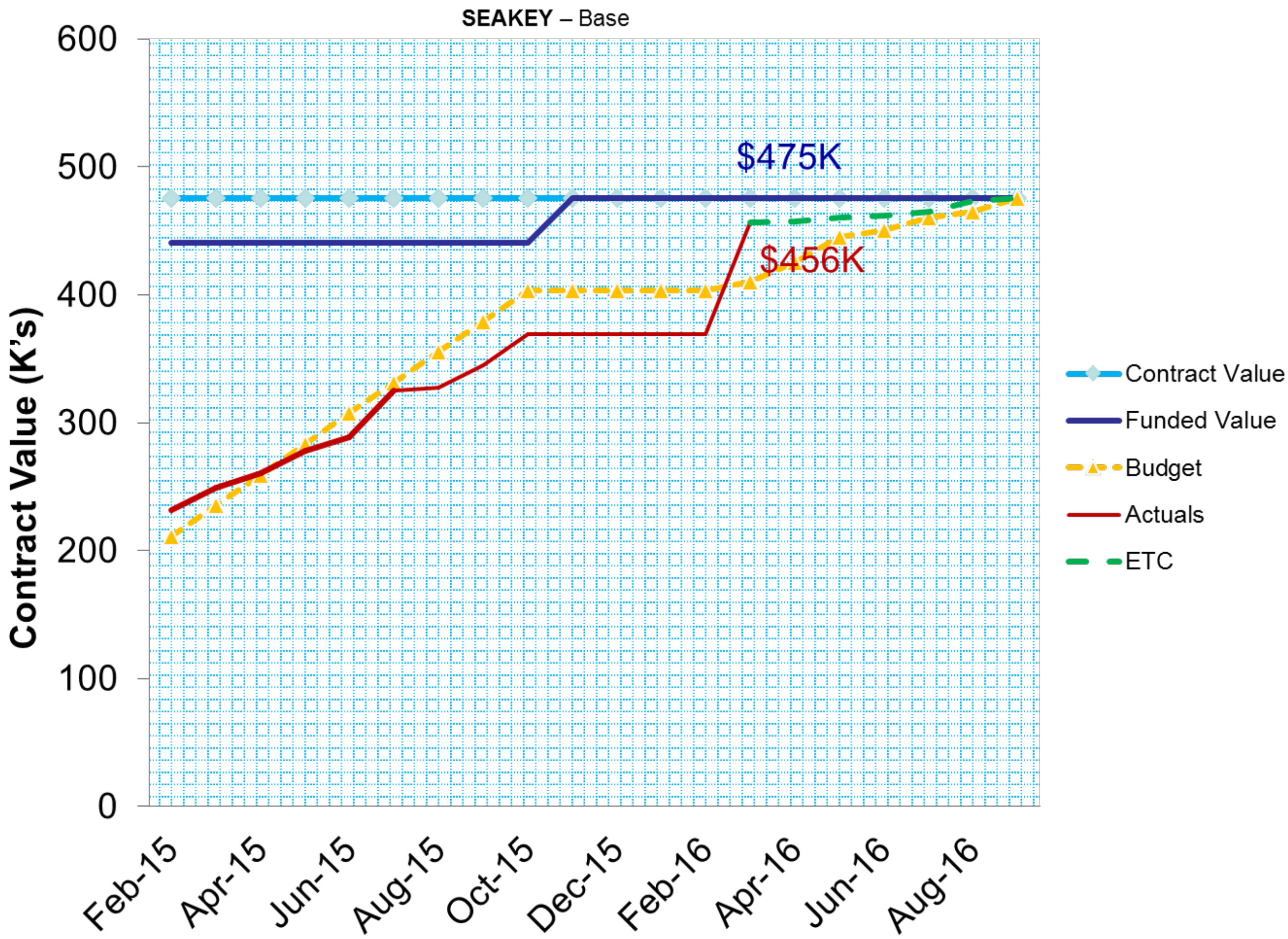
**Next Steps**:

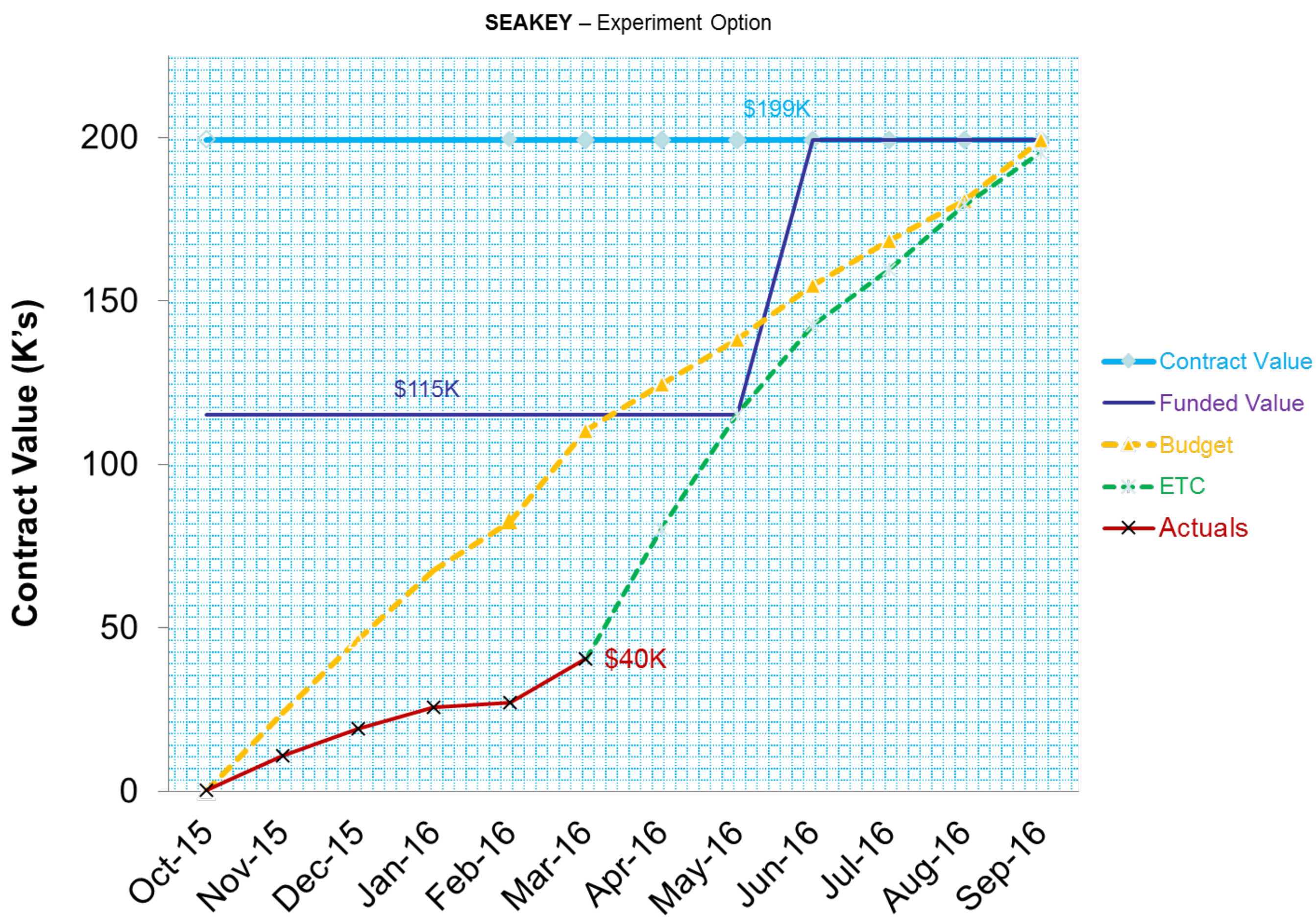
In the next quarter we will be continuing construction of the receiver setup, and providing data to the theorists for examining the performance of the receiver approaching the shot-noise limit. We will also be beginning construction of the QPSK transmitter.

## Section C. Problem Areas – Identification

There are no problems or issues to report at this time.

## Section D.  Financial Update




SEAKEY – Experiment Option
Contract Value (K's)
200
150
100
50
0
$199K
$115K
$40K
Oct-15
Nov-15
Dec-15
Jan-16
Feb-16
Mar-16
Apr-16
May-16
Jun-16
Jul-16
Aug-16
Sep-16
Contract Value
Funded Value
Budget
ETC
Actuals