Oscillator Sources for a DORIS Satellite SDR Receiver System

Benjamin H. Barnum[1], Chris Haskins [1], Wesley Millard [1] , David Rainwater [2], and Michael Kelly [1]

[1]The Johns Hopkins Applied Physics Laboratory, Laurel, MD, USA

[2]Applied Research Lab, University of Texas, Austin, Texas, USA

ben.barnum@jhuapl.edu

Abstract—The global Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) beacon system is currently used to make measurements of the Total Electron Content (TEC) of the ionosphere, satellite position and orbit determination, and measurement of the Total Water Vapor Content (TWVC) of the lower atmosphere. The DORIS network is comprised of a system of over 50 ground beacon stations transmitting a precisely controlled phase-locked, dual frequency (2.036 GHz and 401.25 MHz) signals. The radio signals are delayed by the electron content, and to a lesser extent the water vapor, along the path from the transmitting station to the satellite receiver. This delay is frequency dependent, thereby enabling measurements of the path integrated TEC and TWVC.

The Johns Hopkins University Applied Physics Laboratory and the University of Texas at Austin, Applied Research Lab are working on adapting the space qualified Frontier Software Defined Radio (SDR) for use as a dual band DORIS receiver on a small satellite or cubesat. The reference oscillator used for this system is a critical part of enabling the measurements, and must maintain a minimum Allan deviation of 10^{-11} or better. Higher precision sources enable more precise slant path measurements of the DORIS signals, and some of the smaller scale variations of the ionosphere. We review the oscillator system requirements for the Frontier SDR and relate these to the science goals of the low earth orbit satellite mission to measure TEC, TWVC, orbit position, and smaller scale ionosphere irregularities.

Key words: satellite, software defined radio, Allan deviation, oscillator, cubesat, DORIS

I. INTRODUCTION

Software Defined Radio (SDR) receivers have many diverse applications owing to their ability to be re-programmed in software for particular tasks. The use of SDR's on spacecraft for communication and scientific measurements has quickly grown. Several space missions use these types of radios such as the Radiation Belt Storm Probes, the Lunar Reconnaissance Orbiter, and the upcoming Iridium-Next satellite constellation. In this paper the requirements for a SDR adapted for measurement of the electron content of the earth's ionosphere are described. The electron density in the ionosphere varies depending on time, location, and solar and geomagnetic conditions. The scientific methods used to characterize the ionosphere rely on the ability of the spacecraft instrument to accurately measure radio signals from ground-based dual frequency radio beacons, from a global network of stations known as DORIS described in the next section. These radio measurements onboard the satellite can also be used for determining the orbit position of the satellite. The measurement requirements depend critically on the internal reference oscillator used in the SDR. The satellite oscillator requirements needed for measurement of the ionosphere, orbit determination and position, and other measurements are described in the following sections for a compact, low power radio receiver based on the space qualified Frontier SDR.

II. THE FRONTIER-DORIS SDR

Although Software Defined Radio (SDR) receivers have been around for more than a decade, very few of this type of radio are fully space qualified with proven mission reliability. This section briefly describes the Frontier SDR, which will be adapted for use as a low cost receiver for DORIS radio beacon signals aboard a low earth orbiting satellite.

A. Overview of the Space qualified SDR used as a DORIS beacon receiver

Satellite radio receivers that have been developed and flown for the reception of DORIS ground radio beacon radio signals have been in operation since the 1990's [1]. The current generation of DORIS receivers performs onboard orbit determination, and generates data for the measurement and correction of ionospheric effects. The DGXX receiver, now in its 2nd generation, weighs over 18 kg and uses nearly 25W of power [2]. Our SDR based approach for a satellite DORIS receiver is much more compact and uses a fraction (1/10th) of the power of DGXX, making it attractive for smaller satellite platforms and missions with critical constraints on size, weight and power (SWaP).

The Frontier SDR is a compact, modular designed radio based on a heritage of successful space qualified designs utilizing proven components. The reliability of the components has been proven on several space missions including New Horizons and the Radiation Belt Storm Probes (RBSP). The Frontier SDR uses a FPGA (Field Programmable Gate Array) with a modular slice design consisting of a receiver, exciter, front-end filters and power modules. The Frontier-DORIS configuration is shown in Figure 1. The modular design allows the SDR to be adaptable as a transceiver or a simpler receiver configuration. Since this version is configured as a receiver the exciter slice is not included.

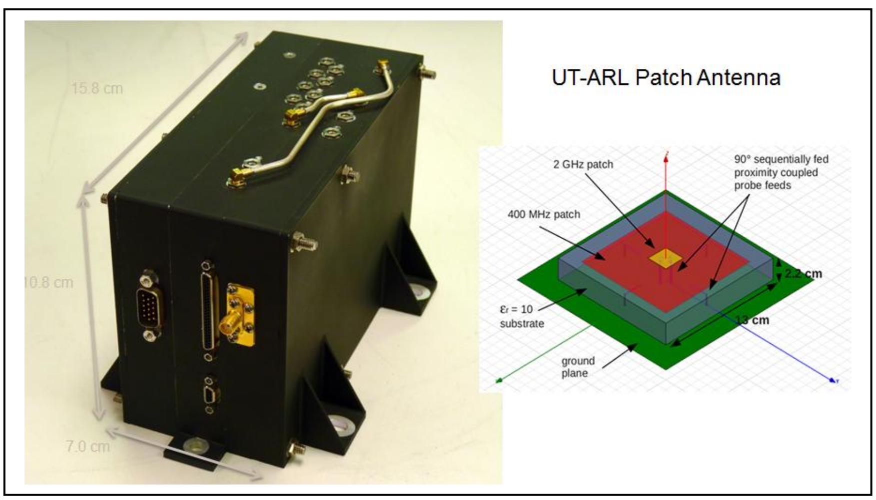

Figure 1. Frontier SDR receiver and patch antenna.

The size, weight and power of Frontier configured as a radio receiver is 7.0cm x 15.8cm x 10.8cm, and uses less than 5W of power [4]. This configuration includes the power converter to operate with typical spacecraft bus voltages. The receiver utilizes an internal 30MHz ovenized crystal oscillator (OCXO). The reference oscillator signal is used in the super-heterodyne design to mix-down the received S-band and UHF radio signals to the IF receiver stages, where the signals are then digitally sampled and input to the FPGA. The full transceiver design is currently being used on the RBSP as the primary radio for communications and navigation. In our proposed application for ionospheric measurements, Frontier would be configured as a dual band radio receiver, without the transmitter module. A compact dual band patch antenna with dimensions of 13cm x 13cm x 2.2cm, shown in at the right of Figure 1, is being designed by University of Texas Applied Research Lab (UT-ARL).

B. Considerations for Frontier Reference oscillator sources

The reference oscillator used in the Frontier radio needs to have high stability in order to enable accurate measurements of the DORIS beacon radio signals. By enabling the accurate counting of the cycles of the received radio beacon signals, the path integrated electron density of the ionosphere can be determined. The effects of the ionosphere need to be measured and corrected in order for accurate Doppler velocity and orbit positions to be calculated. Just how well the receiver is able to perform these tasks depends directly on the quality of the onboard reference oscillator. The DGXX receiver uses a separate ovenized crystal oscillator, which maintains an Allan deviation of 2 x 10^{-13} over 10s. This level of precision matches the performance of most of the DORIS ground beacon station oscillators, and enables orbit determination to the centimeter level. If the needs for precise orbit determination and ionosphere electron density measurements can be relaxed somewhat, then much more compact reference oscillators with Allan deviation of 10^{-11} over 10s to 100s, can be considered. However, in this design, size and power are key considerations because the package would be used on a satellite mission with extreme constraints on power and size. The original mission considered for the Frontier-DORIS design was to be included in a suite of instruments that would have been flown on the upcoming Iridium-NEXT communications satellite constellation, under a science program for hosted payloads known as GEOSCAN [4]. Other satellite missions are now under consideration including use on a 6U (20cm x 10cm x 30cm), or adaptation to a 3U (e.g. 10cm x 10cm x 30cm) cubesat design.

III. IONOSPHERE MEASUREMENTS USING RADIOGRAPHY

This section reviews the basic equations that are applicable to making dual-band radiofrequency measurements of the ionosphere. The main effect on radio signals is caused by the free electrons in the earth's ionosphere. By using two different radio frequencies, measurement of these ionosphere effects can be made and corrected. This correction is necessary when radio beacon signals are used for precise positioning or orbit determination. How well these effects can be measured depends in part on the reference oscillator used on the satellite receiver. The ground based radio beacon system known as DORIS was developed, and is maintained by France's Centre National d'Etude Spatial (CNES). The beacon system allows for precise orbit determination, potentially down to the cm level, which requires the ability to correct for the effects of the ionosphere and atmosphere.

A. Overview of Ionosphere measurements using dual-band radio signals

The earth's ionosphere is a dispersive medium for radio wave energy. At UHF (>300MHz) and higher radio frequencies, the refraction *n* of radio waves is frequency dependent:

$$n = \sqrt{1 - \frac{N_e q_e^2}{m_e \varepsilon_0 4\pi^2 f^2}} \tag{1}$$

The electron density N_e, integrated along the path from the ground station to the satellite, undergoes a greater delay at the lower radio frequencies. The total electron content (TEC), which is the sum of all the electron densities occurring along the radio wave path (r_0 to r_t), is measured by the wave as it propagates from transmitter to receiver:

$$TEC = \left[\int_{\mathbf{r}_0}^{\mathbf{r}(t)} N_e ds \right] \tag{2}$$

By measuring 2 different frequency radio signals from a coherent source, the path integrated or total electron content (TEC) can be measured by comparing the differences in the path delays. The refractive effects are more accurately measured when the 2 radio signals have a wider frequency separation. The DORIS beacon broadcasts a UHF signal at 401.25MHz and an S-band signal at 2026MHz. The satellite measurements using ground beacon radio signals such as DORIS, measure the TEC along slant paths between the transmitting station and the satellite, as shown in Figure 2 below. Other methods are sometimes used for the measurement of N_e and TEC by comparing occulting radio signals between satellites measured over the limb of the earth, as one satellite rises or sets relative to the other, such as in GPS radio occultation (RO) [5]. The Frontier-DORIS system discussed here however relies only on radio signals from ground to satellite offering a direct measurement of the trans-ionospheric path TEC. As the satellite orbit passes over a ground DORIS beacon transmitter, the radio measurements are recorded at successive time intervals along varying slant paths. In low earth orbits (satellite altitudes of 500 to 900km) these transits usually take about 600 seconds or less.

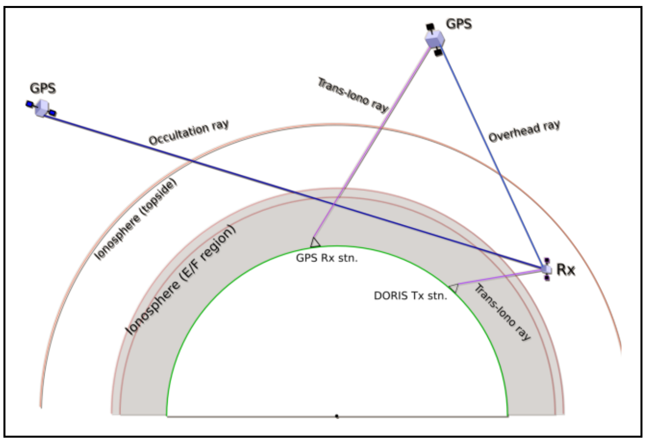

Figure 2. DORIS and GPS Radio signals along transionospheric paths.

The phase delay or number of cycles measured over a time interval t_1 to t_2 during the satellite transit for the lower frequency signal is given by:

$$D_L(t_1,t_2) = (f_L - f_{L,ref})(t_2 - t_1) - \frac{f_L}{c}[\rho(t_2) - \rho(t_1)] + \frac{1}{2}\frac{q_e^2}{m_e \varepsilon_0 c 4\pi^2 f_L}\left[\int_{\mathbf{r}_0}^{\mathbf{r}(t_2)} N_e ds - \int_{\mathbf{r}_0}^{\mathbf{r}(t_1)} N_e ds\right] \quad (3)$$

and for the higher frequency signal:

$$D_H(t_1,t_2) = (f_H - f_{H,ref})(t_2 - t_1) - \frac{f_H}{c}[\rho(t_2) - \rho(t_1)] + \frac{1}{2}\frac{q_e^2}{m_e \varepsilon_0 c 4\pi^2 f_H}\left[\int_{\mathbf{r}_0}^{\mathbf{r}(t_2)} N_e ds - \int_{\mathbf{r}_0}^{\mathbf{r}(t_1)} N_e ds\right] \quad (4)$$

where the beacon's radio signals are transmitted at frequency f_L and f_H and received by the satellite over the radio signal's path ρ(t), using an internal reference frequency $f_{L,ref}$ and $f_{H,ref}$. The cycles are measured as over some time interval t_1 to t_2 as the satellite transits over the beacon. The DORIS dual band radio signals were chosen to have an integer relation between the two frequencies such that f_L = (107/543) f_H . By taking the difference between the high and low frequencies, the relative slant path TEC can be determined from:

$$D_H\left(t_1,t_2\right)-\frac{543}{107}D_L\left(t_1,t_2\right)=\frac{1}{2}\frac{q_e^2}{m_e\varepsilon_0 c4\pi^2 f_L}\left[\frac{107}{543}-\frac{543}{107}\right]\left[\int_{\mathbf{r}_0}^{\mathbf{r}(t_2)}N_e ds-\int_{\mathbf{r}_0}^{\mathbf{r}(t_1)}N_e ds\right] \qquad (5)$$

The last term in equation (5) is the change in relative slant path TEC from the ground beacon to satellite measured between successive position of the satellite at r(t_1) and r(t_2). For precise orbit determination which relies on the measurement of satellite Doppler, the effects of the TEC ionospheric term must be known. The relative TEC measurements can also be used as input to models used for mapping of ionospheric densities such as GAIM and IDA-3D [6,7]. These models are used to derive accurate maps of global TEC, and ionosphere densities which are needed for terrestrial radio propagation at LF (0.3 to 3MHz), HF (3 to 30MHz) and VHF (30MHz to 300MHz) frequencies (Figure 3).

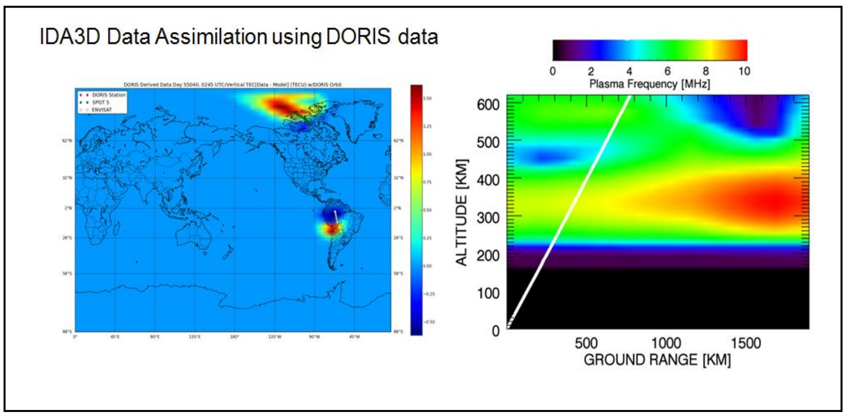

Figure 3. IDA3D ionosphere data assimilation models.

Although the primary focus of dual-band radio orbitography is the measurement and correction for the effects of the ionosphere, some residual effects due to tropospheric water vapor are also present at these frequencies. This effect is small and results in errors in the orbit position of the satellite on the order of a cm or less [10].

B. *The DORIS global beacon network*

The need for precise orbit determination to the centimeter level or better was the motivation for the development of the DORIS beacon network. The system has been used for precise orbit determination and ionospheric correction for radar altimeters on oceanographic survey satellites beginning with the TOPEX-Poseidon mission in 1994, the SPOT satellite missions and continuing with upcoming geodesy satellites planned over the next decade to be flown by ESA, NASA and Chinese Space Agency [8].

The DORIS network is comprised of over 57 stations located at diverse locations around the world roughly located at each 15 degrees of latitude and longitude. The stations all broadcast a coherent phase controlled signal at 401.25MHz (5W radiated power) and 2036.25MHz (10W radiated power), which as noted above, is numerically related by the integer multiple of 107/543. A timing signal is sent every 10 seconds, along with meteorological data, station beacon identification and engineering information. The data is biphase PCM modulated onto the carrier at 200 bits/s.

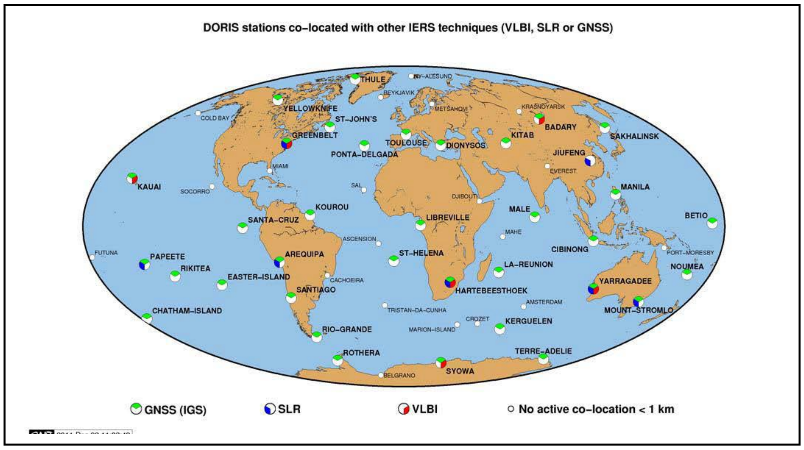

Figure 4. Global network of DORIS beacon stations [8].

Of these 57 stations, there are 11 reference sites using precision ultra-stable oscillators (USO), typically cesium clocks. These sites have been precision located using VLBI surveying, and are collocated with GPS ground receiver stations. The TAI corrected timing of the reference sites can be predicted for a 10 day period to better than 500ns, with other stations reporting daily 500μs accuracy. The DORIS beacons are located at diverse locations around the world including Antarctica, Mount Everest and Le Crozet Island in the Indian Ocean (Figure 5).

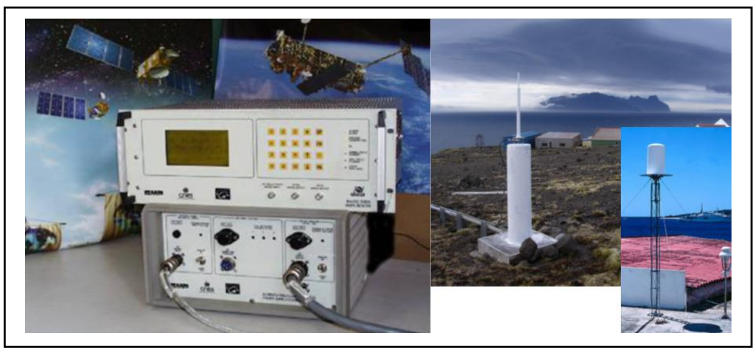

Figure 5. DORIS beacon oscillator and antenna setups [7].

All of the reference stations and many of the other sites have been upgraded using concrete antenna piers, instead of roof mounted towers, shown in the right panels of Figure 5, along with the cesium reference USO and transmitter equipment (left). The oscillator system for this DORIS station has an Allan deviation of 10^{-13} over 10 to 1000 seconds and generates a 5 MHz signal [8].

One of the advantages of the DORIS ground beacons is the addition of ground meteorological instruments which measure the pressure, temperature and humidity at the transmitter location, and include the data as part of the radio beacon signals. These data are sent as part of the data header encoded into the beacon signals and sent every 10 seconds. The station meteorological data aid in more accurate overall estimation of the tropospheric delays over these locations and for the retrieval of the absolute integrated total water vapor [11]. To date real-time retrieval of the wet tropospheric delay has not been done using DORIS satellite signals; however, the post-processed data using the newer referenced stations has shown comparable results to GPS measured values [12].

C. Satellite Receiver Oscillator Requirements

The Frontier SDR that is being adapted to receive DORIS beacon signals must be able to accurately measure the phase of the 401MHz (f_L) and 2035MHz (f_H) radio signals. The DORIS signals have a timing mark which is broadcast every 10 seconds along with the station data. Typically the signals are measured over this 10 second frame interval. By comparing the cycle counts between the two signals over this interval, the relative TEC can be measured using equation 3. Ground Global Navigation Satellite System (GNSS or GPS) stations can measure relative TEC values with an uncertainty of 0.7 TEC units, where 1 TEC unit = 1 x 10^{16} electrons/m^2. GNSS measurements also have some additional uncertainty of 1 to 3 TEC units due to contributions due to the higher altitude orbit of the satellites, which gives a plasmasphere contribution in addition to the ionosphere [12].

Based on equation 5 above, an estimate of the uncertainty in the relative TEC measurements can be made:

$$\frac{D_L(t_1,t_2)-\frac{1}{5}D_H(t_1,t_2)}{\frac{1}{2}\frac{q_e^2}{m_e\varepsilon_0 c 4\pi^2 f_L}}=\left[\int_{\mathbf{r}_0}^{\mathbf{r}(t_2)} N_e ds-\int_{\mathbf{r}_0}^{\mathbf{r}(t_1)} N_e ds\right] \tag{6}$$

By computing the value for the denominator in (6), a value of 3.36 x 10^{-16} is found, and 1 TEC unit will give approximately 3.3 cycles of change between f_L and f_H. Assuming that the Frontier radio can easily determine a 1 radian phase difference between the two frequencies, then the TEC would be measured within +/-0.5 TEC units. The reference oscillator however must generate a stable reference for both the low and high frequency, and the higher frequency will drive the overall oscillator requirement with a frequency variation $\delta f/f$ no greater than ~8 x 10^{-11} over 10 seconds as a minimum. This level of performance is comparable to space based oscillators that were used on the Navy Navigation Satellite, which had an Allan deviation of ~10^{-10} over t = 10s [9].

Orbit determination drives similar and even more stringent requirements on the receiver's oscillator. At Low Earth Orbit (LEO) with an altitude of 700 to 900km, the satellite will have an orbital velocity of roughly 7 km/s. In order to measure the on orbit track position to centimeter accuracy requires accurate timing within ~1.4 µs. The broadcast timing signal from DORIS ground beacons without correction is +/-50µs, which sets a lower limit on the track error that can be measured without post-processing corrections [13]. Cross orbital track errors have been previously estimated by Newton [6] and others, and are estimated as 2 x $10^8(\Delta f/f)$ meters. An oscillator with a drift of 10^{-10} over the satellite's transit would give an error of up to +/-2cm. The minimum approach distance of a satellite is determined by the time at which the Doppler frequency measured at the satellite is a minimum or zero. The Doppler rates also give the range rate and minimum range rates (dr/dt, and d^2r/dt), used in orbit and position determination. Geodesy applications typically require orbit and position determination to the centimeter level or better, thus driving oscillator requirements to Allan deviations of 10^{-11} or 10^{-12} or more.

The ionosphere corrections detailed above provide over 100 meters of correction to the satellite position, making it critical for accurate position and orbit determination. There still remains a residual delay of the radio signals due to the neutral atmosphere and water vapor [6, 11, 12]. The troposphere delay which is present in the DORIS and GPS dual band radio signals is known as the Zenith Tropospheric Delay (ZTD). ZTD consists of both the atmospheric term, or Zenith Hydrostatic Delay (ZHD), and the zenith water vapor delay (ZWD) for a vertical path. The hydrostatic delay term can be readily calculated at locations where the surface pressure is known, which it is at all DORIS stations. The total precipitable water can be estimated from ZWD, and is simply 1 mm of PWV per 6.55mm of measured ZWD. It should be clear that the determination of these quantities pushes the requirements for orbit position to the centimeter level driving the oscillator requirements. Geodesy and the determination of tropospheric water vapor require the highest oscillator precision in order to obtain millimeter level orbit position, and data post processing in order to do the corrected calculations necessary. The oscillator requirements must nearly match the ground beacon station, with Allan deviations of 10^{-13} over 10s. A summary of the oscillator requirements is given in Table 1 below.

Table 1. Satellite oscillator requirements for DORIS measurements.

Measurement	**Error ranges**	**Allan Deviation**
TEC	0.3 TEC units (0.3 $\times 10^{16}$ e^- per m^2)	10^{-10} (10s)
POD	meter/cm/mm	10^{-10} to 10^{-13} (10 to 10^4 s)
ZTD	+/- 4 mm	10^{-12} to 10^{-13} (10-100s)

The reference oscillator requirements for the Frontier-DORIS receiver at this time are primarily focused on minimizing the instrument's SWaP, while maintaining the highest level of measurement accuracy. At a minimum, the receiver must be able to measure the ionosphere relative TEC to better than 0.3 TEC units, with orbit determination to the meter level. Based on these requirements, a reference oscillator that can maintain an Allan deviation of 10^{-11} over 10s to 100s is sufficient. The oscillator radiation tolerance for LEO altitudes requires up to 100 kRads. A thermally controlled, compact low power oscillator is part of the baseline Frontier radio design shown in Figure 8 below. The space grade oscillator is radiation tolerant, and uses less than 1W of power, in a package less than 2.5cm x 2.5cm.

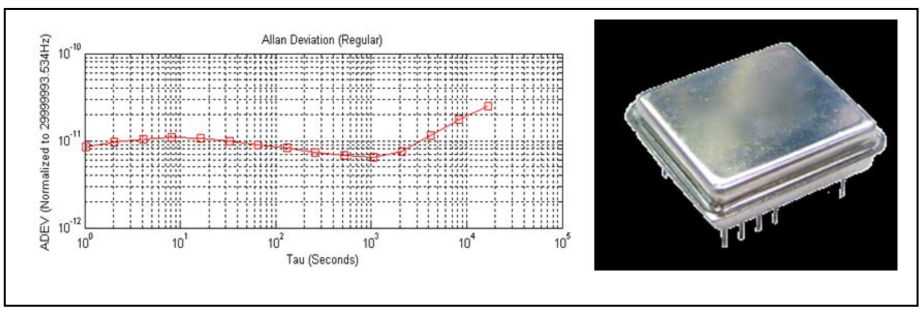

Figure 6. Frontier-DORIS compact ovenized oscillator.

For higher precision measurements, a fully ovenized ultra-stabilized oscillator (USO) would be needed. Space qualified oscillator systems developed and flown by the Johns Hopkins Applied Physics Laboratory include USO's for the GRACE and CASSINI missions. Newer versions of these USO's typically use 3W of power, weigh roughly 1.5kg and would have to be housed separately from the Frontier SDR package. These oscillators could provide radiation tolerant sources with Allan deviations of only 2 x 10^{-13} over 10s, nearly 2 orders of magnitude better than the compact ovenized source, and matching the performance of the DORIS ground reference stations.

IV. CONCLUSION

A compact space qualified SDR is an excellent option for a satellite DORIS receiver. This type of radio offers an efficient compact design for use as on a greater variety of satellites in low earth orbits. DORIS signals offer a robust way to measure the electron content of the ionosphere, and also for spacecraft position and orbit determination. Current space qualified oscillators with suitable radiation tolerances and stability can fit inside the Frontier SDR package. The ovenized oscillator that is part of Frontier-DORIS design will enable orbit determination down to the meter level, and relative TEC measurements with an accuracy better than ground based GPS receivers (i.e., < 0.3 TEC units).

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