GSN Primary Sensor Tests at Black Forest Observatory

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Introduction.

This document is to summarize recent primary VBB sensor instrument tests that ASL and IDA have conducted in cooperation with the staff of the Black Forest Observatory (BFO) in Schiltach, Germany. BFO is a geophysical observatory jointly operated by the University of Stuttgart and the Karlsruhe Institute of Technology situated in an abandoned silver mine in the mountains of southern Germany. BFO hosts an affiliated GSN station whose data are distributed under the code II.BFO and whose instruments include a set of STS-1 VBB seismometers, a LaCoste-Romberg gravimeter, a superconducting gravimeter, plus associated tiltmeters, strainmeters, microbarometers and magnetometers. BFO also hosts an

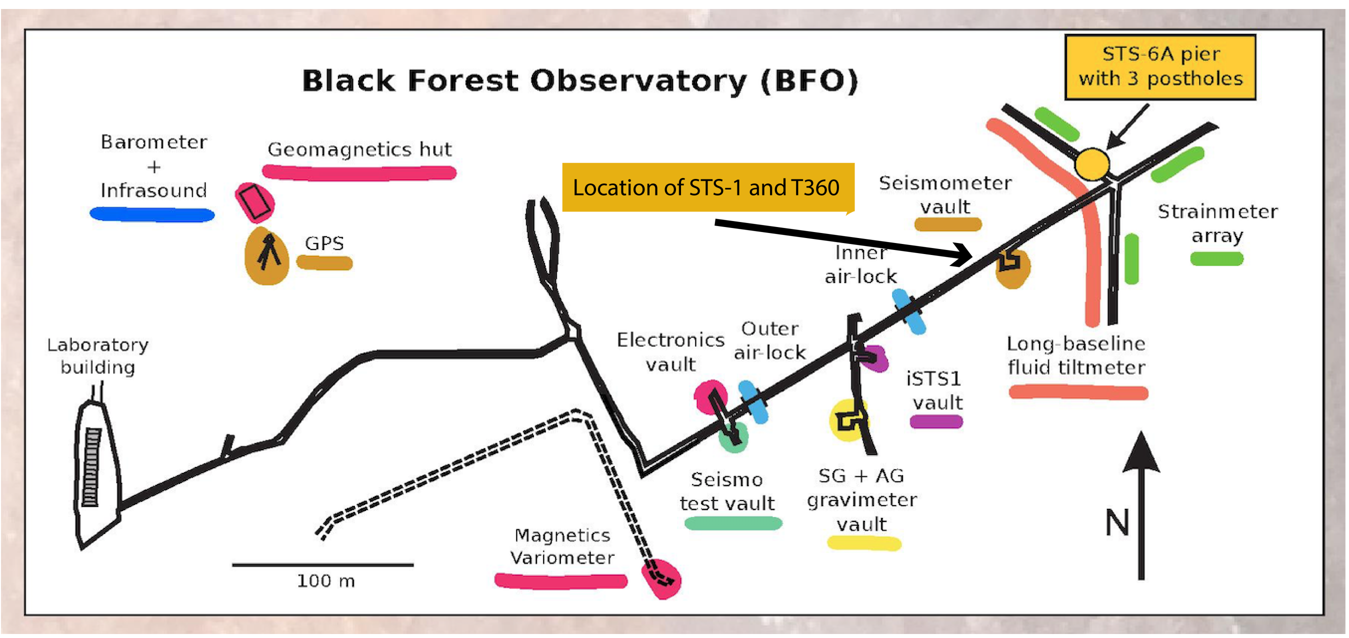

Figure 1. Map of the BFO mine. Behind the dual air-lock is the seismometer vault with the STS-1 and STS-2 seismometers. In the very back and next to the N300E strain meter is the new pier with the three boreholes where the STS-6As are deployed. Map courtesy of R. Widmer-Schnidrig.

STS-2 sensor whose data are distributed as GRSN station GR.BFO. The observatory is world-renowned for low seismic noise conditions at long periods.

ASL was interested in investigating new vault installation techniques. To this end, a USGS team visited BFO and drilled one 1.6m deep borehole into the floor of one of the mine's vaults and began a second hole. At this point the BFO staff took over and completed the second hole and added a third hole. ASL supplied two STS6A sensors for testing, and Streckeisen GmbH provided a third unit. All data were recorded on high resolution (26-bit) channels of two Q330HR and were streamed to the IRIS DMC for processing by standard MUSTANG quality control routines.

Figure 2. Photos of the STS-6A installation in the tunnel at BFO. The left photo is a view aligned downhole showing the coring through the pad into the bedrock below. The center photo shows the pad with two of the three holes open and visible. In a matter of hours the holes filled with water (visible in the both open holes). The concrete cylinder to the left was used in the installation as described below, an STS-6A is standing on the pad to the right of the cylinder, and a third, yellow cylinder covers the third hole into which one of the STS-6As was installed.

IDA's aim was to evaluate the performance of a prototype T360 vault sensor supplied by Nanometrics for the purpose. To support the test, UCSD provided a GSN Q330HR to BFO on temporary loan. Like the STS-6As, all data were recorded at 26-bit resolution and streamed to the DMC.

Details of the Instrument Deployment

STS-6A sn 176254 – data streamed as II.XBFO.50.*

2018.09.16 - Installed in hole drilled into granite; stainless steel cylinder 7" OD placed into coal slag; sensor inside cylinder packed with sand blasting abrasive.
2018.12.20 - changed to Q330HR sensor A SN 5985

STS-6A sn 150804 – data streamed as II.XBFO.55.*; prototype from Streckeisen without the built-in mu-metal magnetic shielding

2018.10.12 - original installation in concrete cylinder with no cover and installed outside of air lock
2018.11.07 – moved sensor inside the air lock; placed cover of cotton and gold foil on top; placed surrounding concrete cylinder on cinder blocks
2019.01.28 – installed instrument in hole with change in media and cover on top

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STS-6A sn 176241 – data streamed as II.XBFO.60.*

2018.10.12 - installed in cement cylinder standing on pier outside of air lock; quartz sand surrounds sensor
2018.11.19 – relocated sensor behind air lock
2018.12.20 - change of DAS
2019.01.28 – discovered hole had filled with water so pumped out water; installed seismometer in hole but ran out of sandblasting media so substituted other sand; added cover on top
2019.04.05 – removed seismometer from hole and installed in sand-filled concrete cylinder on top of pad.
2019.04.11 – reinstalled seismometer in hole with fresh media that has low cohesion; filled steel pipe with aluminum oxide and corundum

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T360 sn 52 -- data streamed as II.XBFO.70.*

2018-08-09 – initial install of sensor next to the GRSN STS2 and the STS1-E. (The STS1-N is installed on a pillar built against the opposite wall.) First attempt was unsuccessful due, it turned out, an incorrect firmware version in the sensor.
2018-08-14 – after firmware upgrade, data began streaming to the DMC.
2018-09-18 – data flow was interrupted when BFO staff swapped out the Q330HR recording the sensor.

STS-6A Test results

The test results for the STS-6A sensors will only be covered briefly and are only mentioned here as they relate to analysis of the T360 seismometer. These sensors were installed in a variety of configurations as noted above, and their performance varied over the period detailed here due to these changes. One assessment of noise performance uses the MUSTANG noise-mode-time series metric. This metric is plotted in Figure 3 from Nov 1, 2018 – Sept. 25, 2019 for

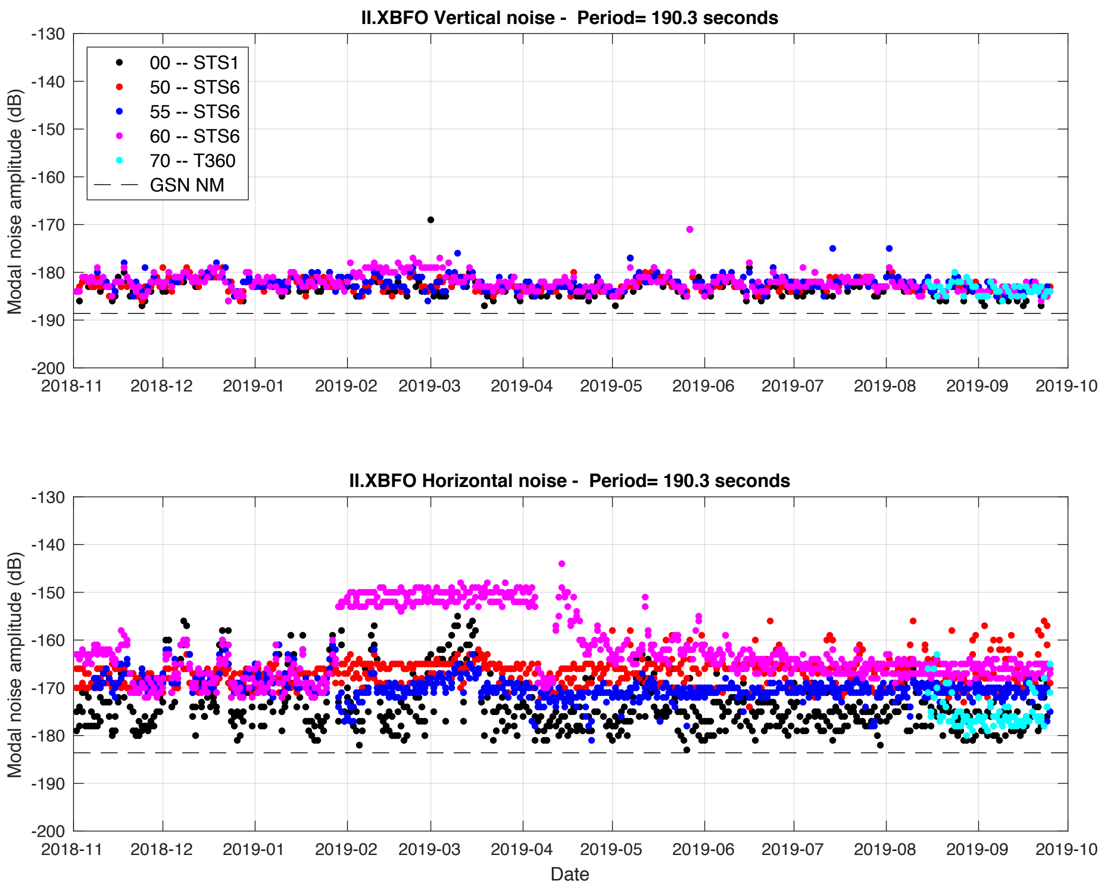

Figure 3. MUSTANG mode-noise-time series metric at period 190sec for the three STS-6A sensors, the T360 vault sensor and the permanent STS-1 sensor. Vertical noise is shown in the upper panel, horizontal noise in the lower.

the single period 190 seconds. The noise level of the vertical component for all three STS-6As remained stable throughout the test and is comparable to the STS1 permanently installed at BFO. The horizontal levels varied depending upon the installation. Most pronounced was the increase in noise on unit 176241 (loc=60) from Jan 28 until Apr 4 due to a poor choice of insulation sand. This problem was corrected one week later, and the noise level fell. However in general, the

STS-6A horizontals did not match the low noise level of the STS-1 horizontals at this frequency.

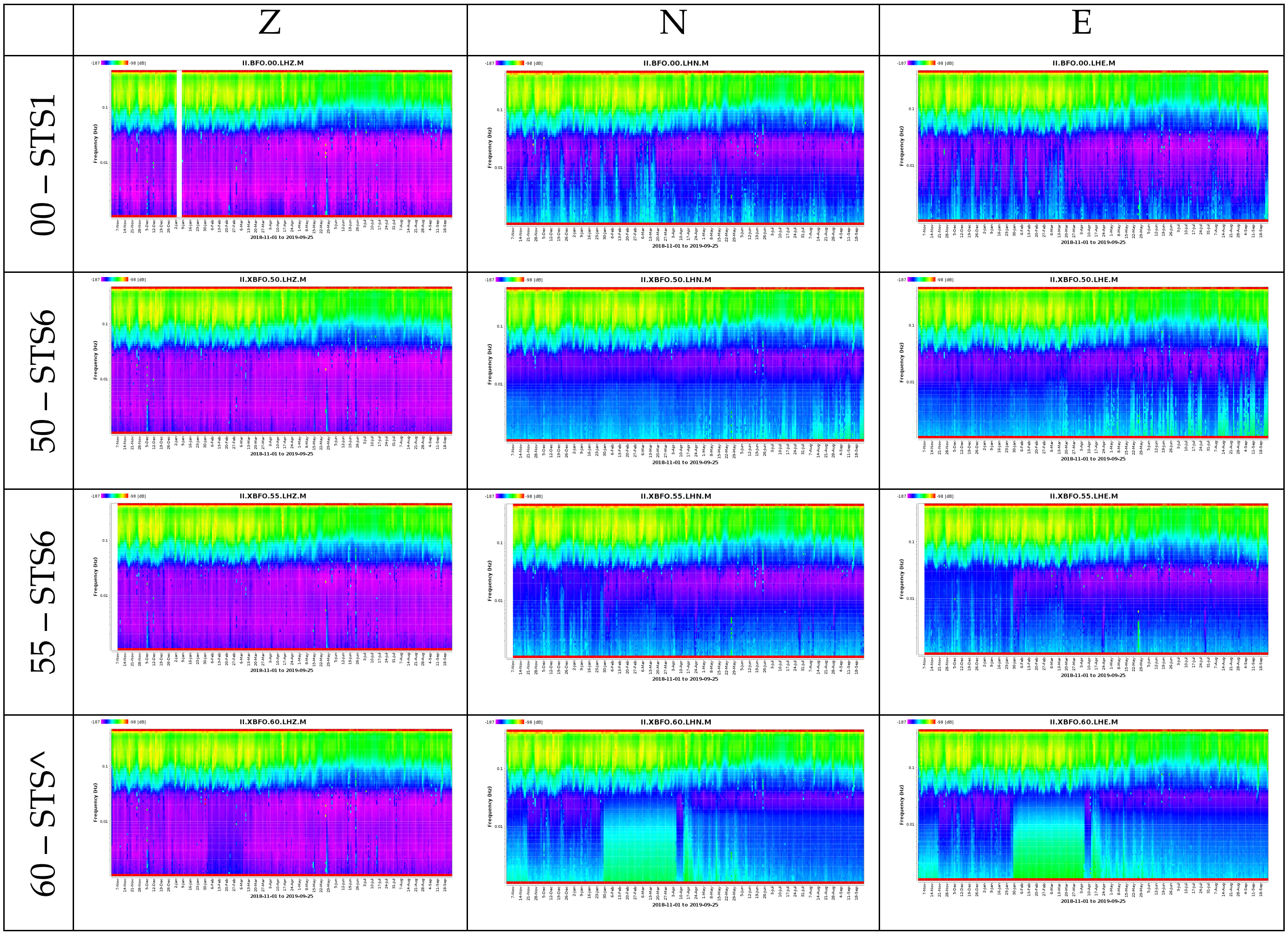

Figure 4. Spectrograms computed using IRIS MUSTANG's noise-spectrogram metric for the period Nov 1, 2018 through Sept. 27, 2019 for the STS-6A sensors as well as the permanently installed STS-1. Full resolution subplots are made available on Dropbox.

Spectrograms computed using IRIS MUSTANG's noise-spectrogram metric are plotted in Figure 4 for this period. These give a broader performance evaluation for these instruments during the period leading up to deployment of the T360 in August.

T360 test results

The following results were assembled by tapping into IRIS MUSTANG's noise-pdf metric. Details of this method can be found at http://service.iris.edu/mustang/noise-pdf/docs/1/help/ . IRIS provides

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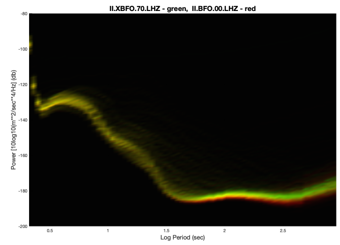
<td>
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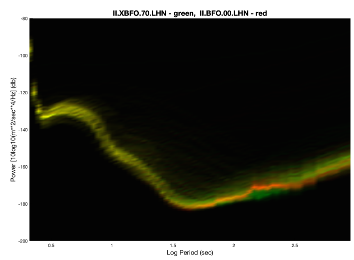
<td>
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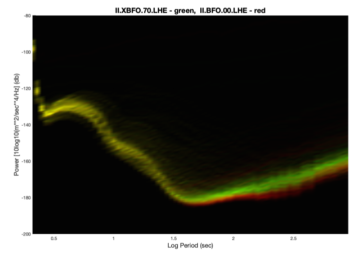
<td>
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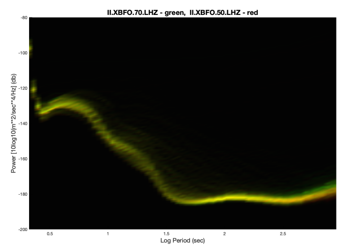
<td>
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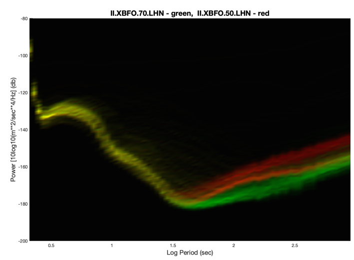
<td>
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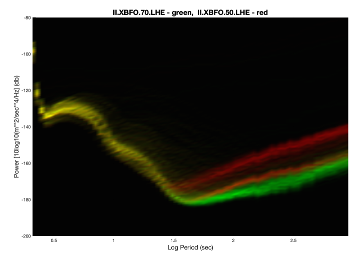
<td>
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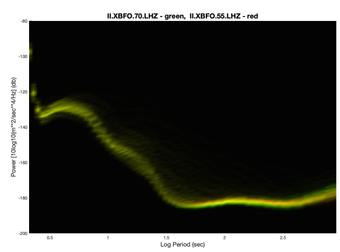
<td>
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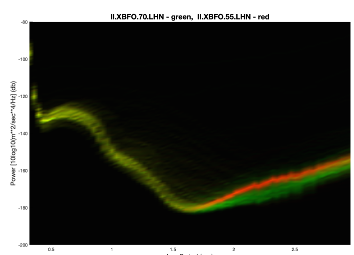
<td>
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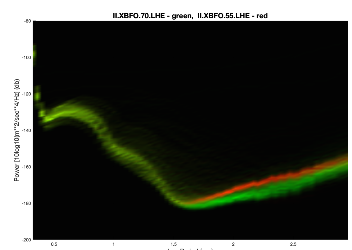
<td>
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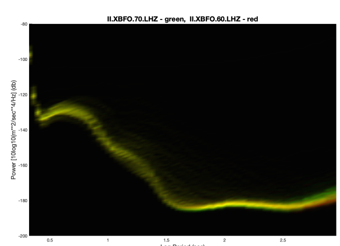
<td>
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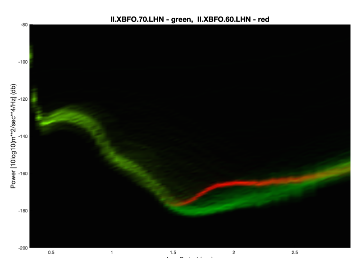
<td>
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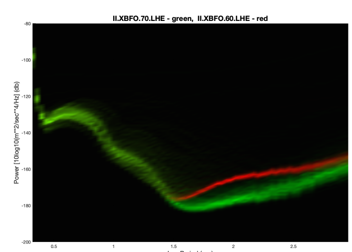
<td>
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Figure 5. PDF results for T360 plotted along with other instruments deployed at BFO. T360 PDFs are in green; the comparison sensor PDFs are in red; and overlaps are in yellow. See link at the end for access to full resolution plots.

the capability to download the raw bin numbers which were done for both the T360 as well as the other instruments deployed there (permanent STS1 and the three STS6s). These PDFs are then plotted for pairs of sensors together (matching appropriate components) on the same figure for easy comparison. All plots were drawn for data collected from Aug 17 to Sept 14. The PDF for the T360 is plotted in green; the instrument being compared to is plotted in red; where the two overlap appears in yellow

PSD results:

Plots in Figure 6 were computed using the method of Berger *et al* (2004). PSDs are computed for 3-hr-long windows over the test period, Aug 15-28, and then sorted at each frequency. The power value of the lowest 5th percentile is then plotted at each frequency.

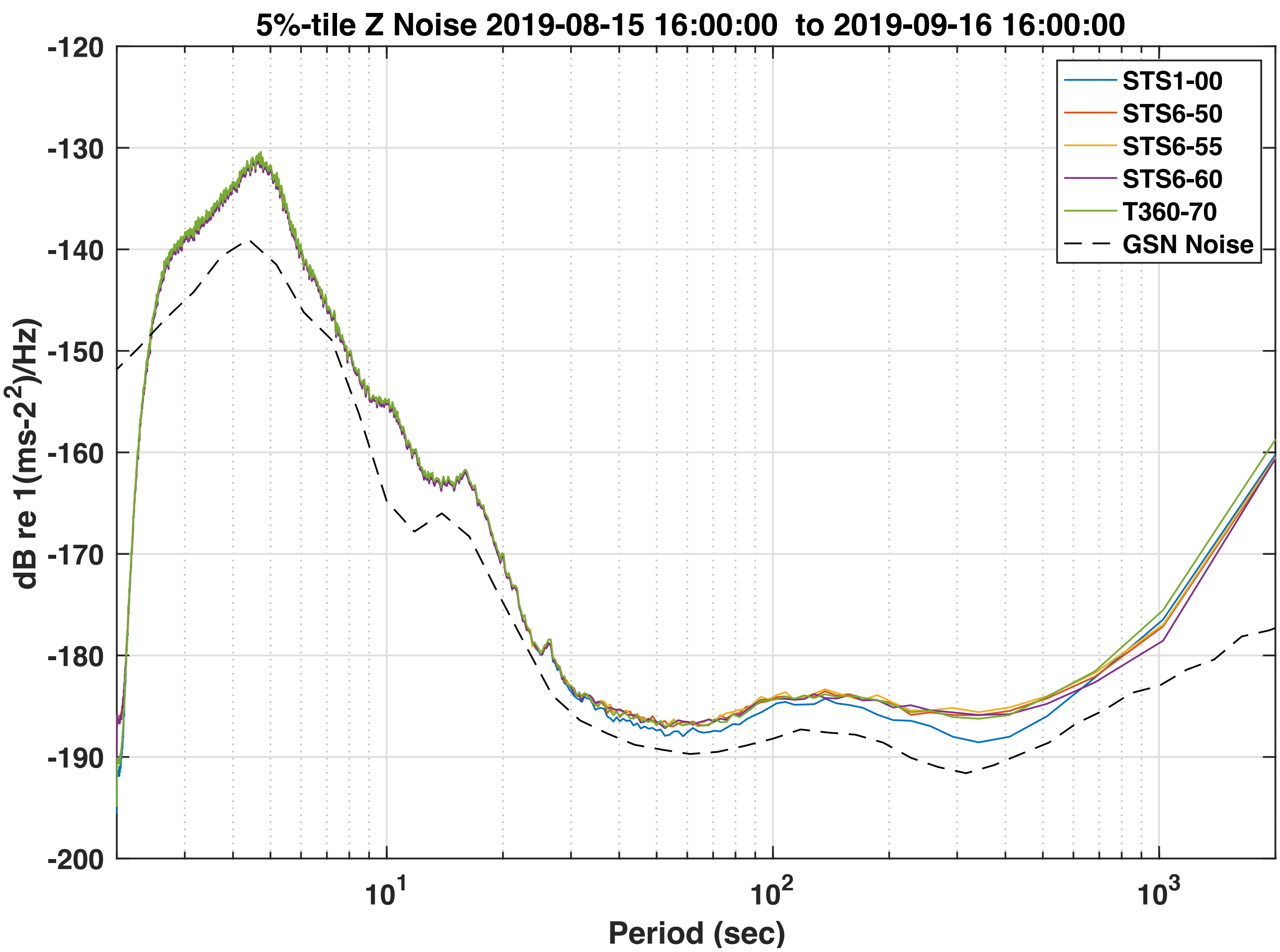


Figure 6a. PSD results for the vertical sensors at BFO. Data plotted are for the 5th percentile at each frequency computed from 3-hr-long windows of LH data. Data are drawn from the time period listed in the title.

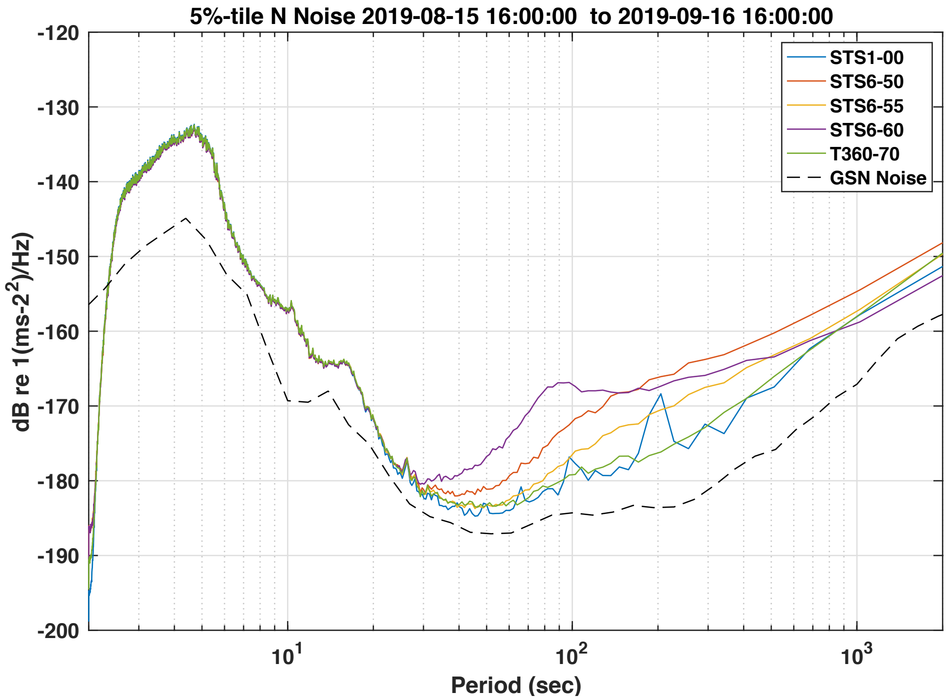


Figure 6b. PSD results for the NS horizontal sensors at BFO. Data plotted are for the 5th percentile at each frequency computed from 3-hr-long windows of LH data.

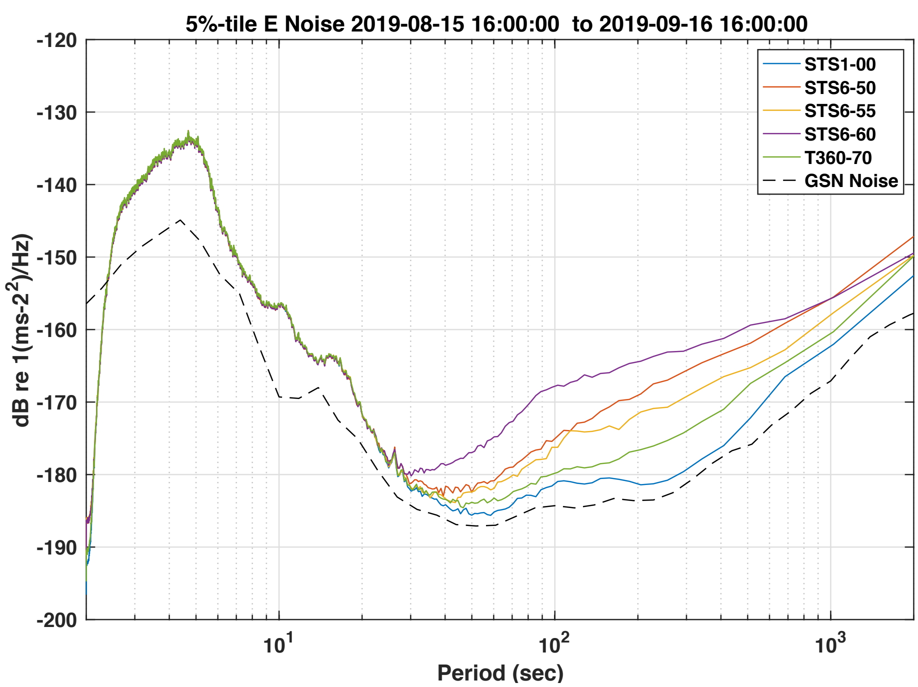
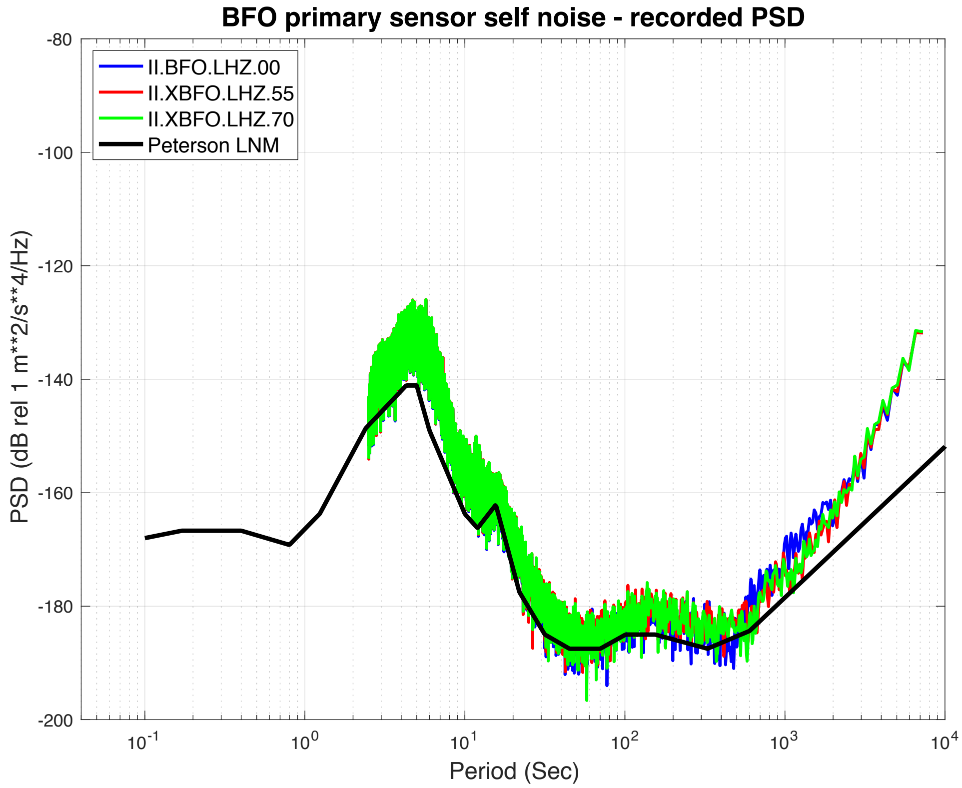


Figure 6c. PSD results for the EW horizontal sensors at BFO. Data plotted are for the 5th percentile at each frequency computed from 3-hr-long windows of LH data.



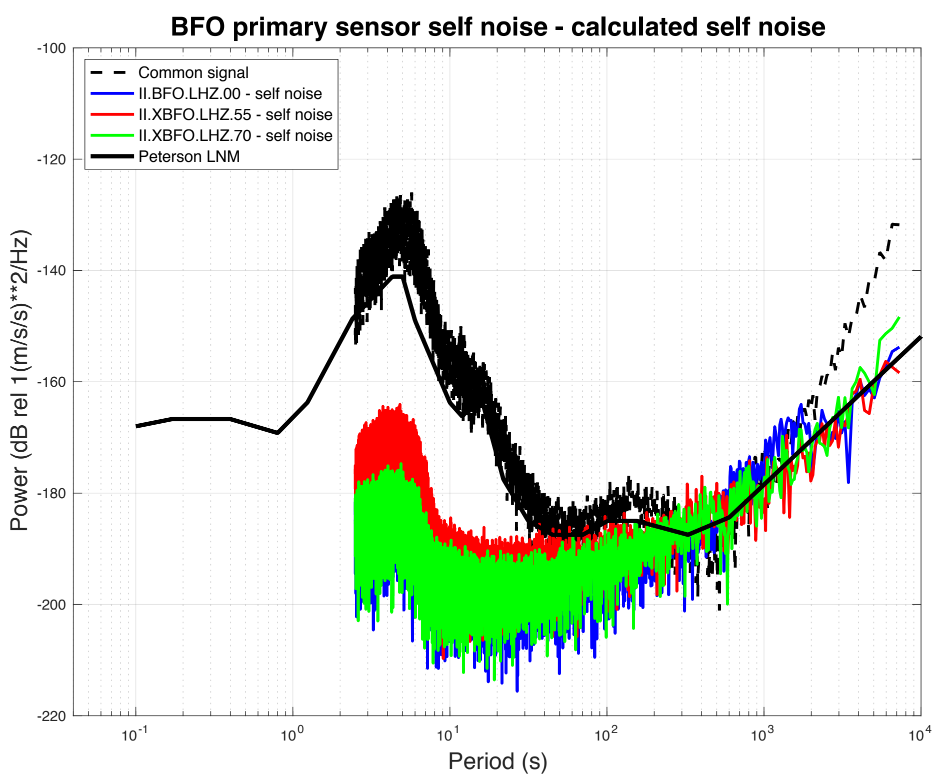


Figure 7. Instrument self-noise computed using the method of Sleeman *et al.* (2006) using the STS-1, one of the STS-6A units and the T360 for the time period Aug 25-27, 2019. PSD for the three sensors is shown on the top plot. Self-noise for the three is shown on the bottom plot.

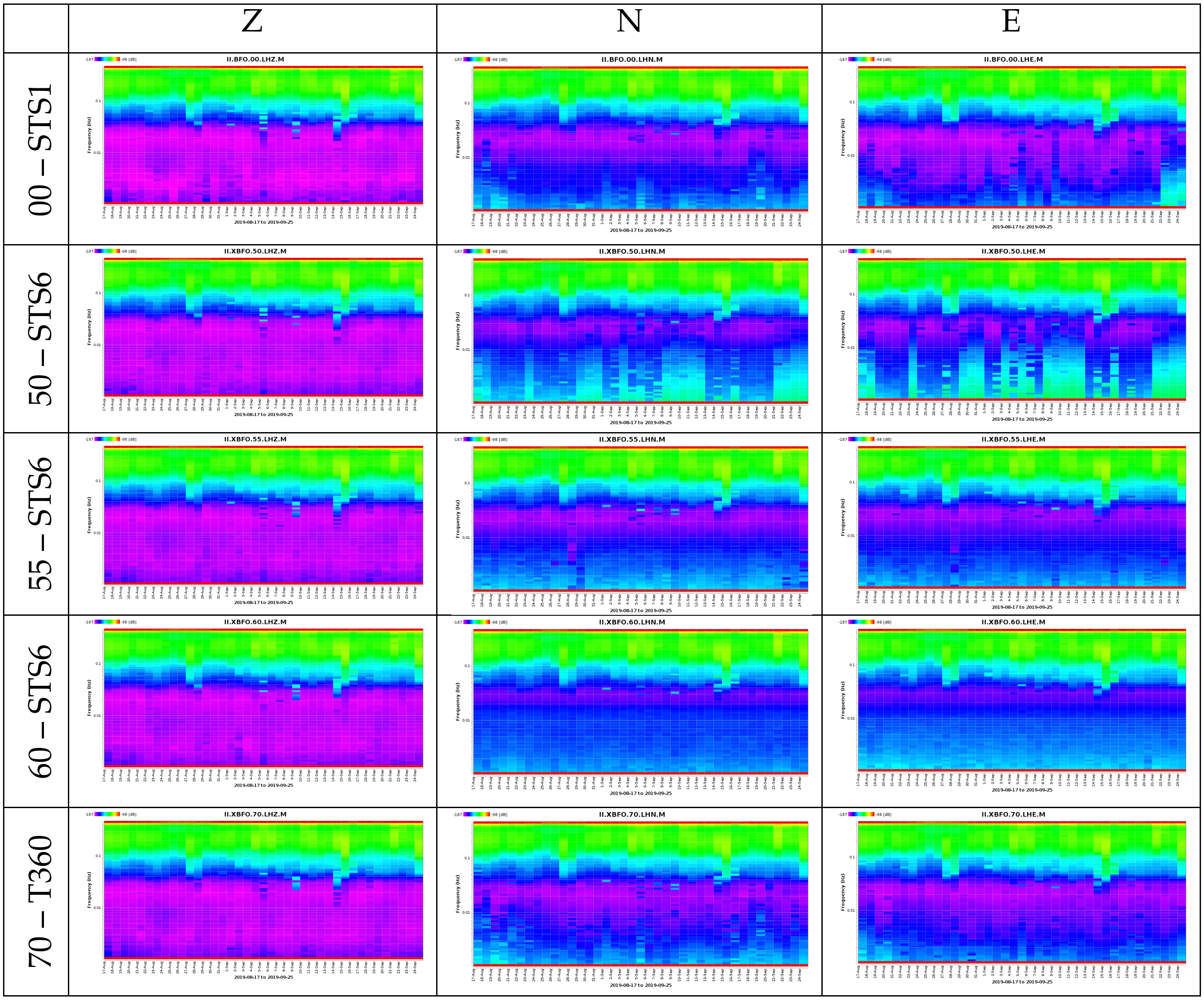


Figure 8. Spectrograms computed using IRIS MUSTANG's noise-spectrogram metric for the period Aug 17 -- Sept 25, 2019. Full resolution subplots are made available on Dropbox. See link at the end.

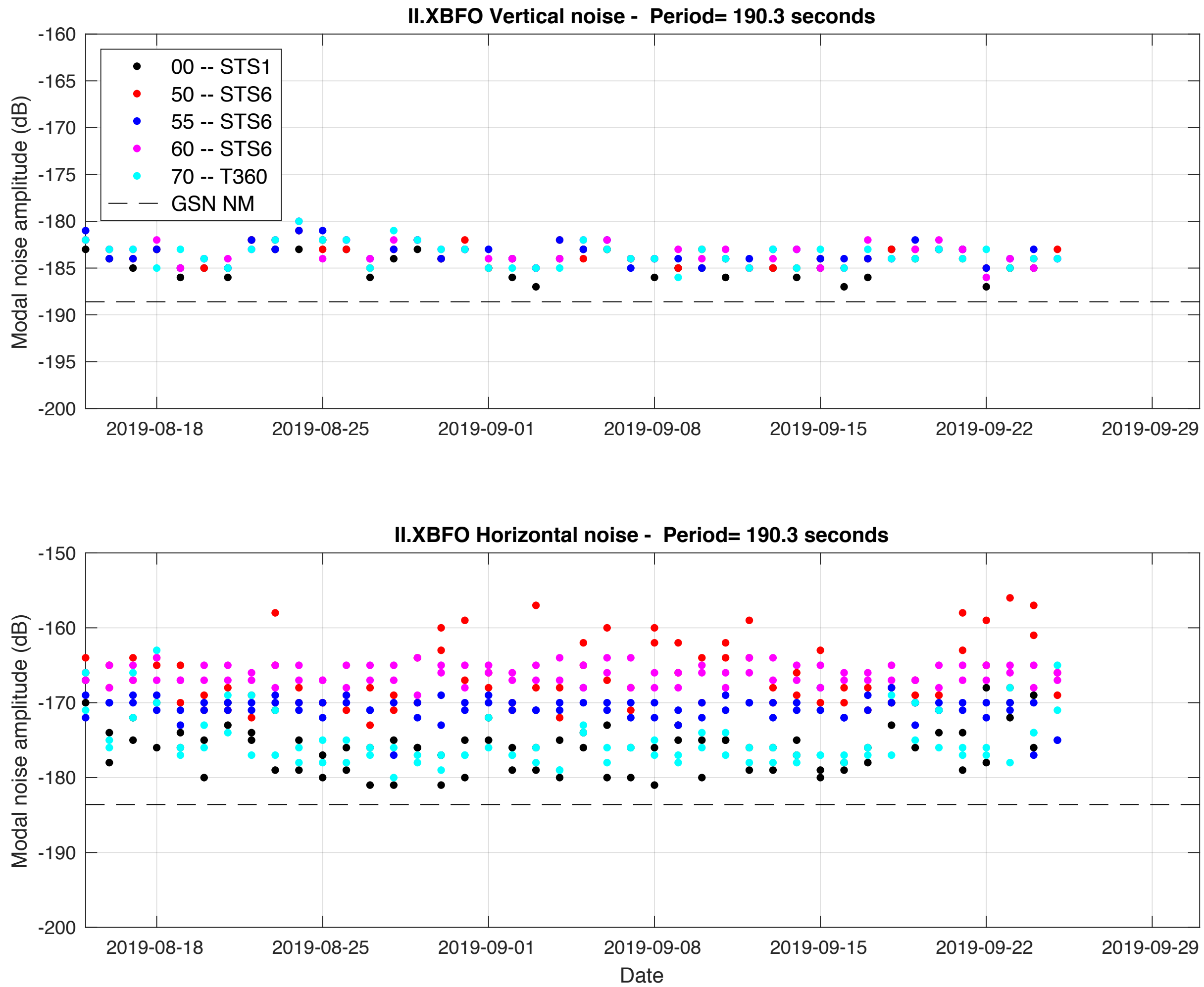


Figure 9. Same as Fig 3 above but for period of T360 testing.

Discussion

The above measurements provide important information that bears strongly on two questions considered in this study: (1) How well does the T360 vault sensor perform compared to the STS-1? (2) How well does the T360 in a traditional pier deployment compare to STS-6As in a posthole deployment? Of the figures above, the most compelling evidence is in Figure 5 in which are displayed the conventional PSDs computed by MUSTANG for the sensors under test.

Because the T360 (and the STS6As for that matter) are Galperin-style instruments, recordings of the vertical give the best indication of sensor self-noise. Recordings of the horizontal components are not limited by sensor self-noise but are more strongly affected by installation issues. The PSDs in Fig. 5 show that on average, the STS1-V is about 1.5 dB quieter at 50s, 2 dB quieter at 100s and 3 dB quieter at 1000s. The T360 matches all the STS6As out to 500 sec at which point two of the three STS6As are on average 3dB quieter and the third unit is comparable. These measurements are consistent with the noise-mode observations plotted in Figure 9. There is a good possibility that these differences at long periods will diminish somewhat the longer the T360 is left undisturbed. In the current setup, the STS6As were in their configuration for five months or more while the T360 data are drawn from the first six weeks since installation.

The standard Sleeman self-noise computation indicates that the T360 self-noise is below the Peterson LNM out to almost 10,000s. Unfortunately, there were many significant earthquakes that occurred during the test period, so it was difficult to find more than one quake-less period to use in this computation.

As regards the second question, the results for the horizontal elements show that, in this testing environment, the T360 mounted on the pier performed much better than the STS6As installed in what has become the standard GSN vault posthole configuration. On average, the T360 was 9 dB quieter than the STS6As at 100s and 6 dB at 1000s.

Conclusions

The above measurements of the T360's performance in this setting indicate:

1. The T360's vertical noise floor is near to that of the STS-1 and comparable to the STS-6A units tested here.

2. The T360 horizontal components perform as well or better than the STS-6A units' horizontal components under these tests.

3. The T360's self-noise follows the NLM out to 10,000 seconds.

Hi-res copies of all figures in this report as well as supplementary plots can be found at:

https://www.dropbox.com/sh/2hyha64zblle7sl/AACq7KqqdhU60DTiPSJ5Ju0ma?dl=0