Interference Potential of the 140-ft Telescope's 7.2075 GHz RadioAstron Transmitter

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In anticipation of a maser failure on the RadioAstron satellite, estimates were made of the effects of the RadioAstron 7.2075 GHz reference tone on the C- and X-band receivers of the Green Bank Telescope (GBT). This memo presents GBT receiver temperature estimates given a variety of telescope orientations, describes results from transmitter tests conducted using the GBT and 140-ft, and provides a brief safety assessment of the 140-ft transmitter's radiation.

GBT Receiver Temperature Estimates

To devise an effective plan for measuring the impact of the RadioAstron transmitter on the GBT's receivers and to avoid damaging the receivers, rough estimates (within a few orders of magnitude) were made of GBT receiver temperatures for a 2W isotropic transmitter on the 140-ft telescope given various telescope orientations. These orientations and resulting system temperatures are given below:

1. On-axis 140-ft as seen by on-axis GBT:
   This orientation, in which the 140-ft main beam and the GBT main beam are perfectly aligned, is impossible. Estimated $T_{sys} \sim 10^{22}$ K·Hz.

2. Isotropic 140-ft as seen by GBT at 5° elevation and pointing directly in azimuth at the 140-ft:
   In this orientation the GBT sees the 140-ft radiating via scattering off of feed legs and other structures as opposed to seeing the 140-ft's feed directly. Restrictions on the GBT can be applied to prevent this orientation. Estimated $T_{sys} \sim 10^{17}$ K·Hz.

3. Isotropic 140-ft as seen by an isotropic GBT:
   The most common orientation during routine operation of both the GBT and 140-ft is likely when the 140-ft is in a far sidelobe of the GBT's main beam. Estimated $T_{sys} \sim 10^{7}$ K·Hz.

4. Isotropic 140-ft as seen directly by the GBT's feed:
   T_{sys} values depend on the position of the 140-ft within various sidelobes of the GBT feed. Estimated $T_{sys} \sim 10^{10}$ to 10^{12} K·Hz.

5. Sidelobes of the 140-ft feed as seen by an isotropic GBT:
   Estimated $T_{sys} \sim 10^{7}$ to 10^{11} K·Hz.

6. Sidelobes of the 140-ft feed as seen by the sidelobes of the GBT feed:
   Estimated $T_{sys} \sim 10^{13}$ to 10^{19} K·Hz .

[1] This is an updated version of the October 21, 2014 Memo that includes Ku-band tests from August 14 2015.

Orientations 3 - 6, and especially 3, are likely the most common for routine operation of both telescopes as they pertain to a wide range of positions for both telescopes. Restrictions to prevent these common orientations would likely be difficult while maintaining sufficient usable sky coverage.

RadioAstron Transmitter Tests

On Wednesday, September 24, 2014, we performed tests to determine the effect of the 7.2075 GHz RadioAstron uplink transmitter on the GBT C-band and X-band receivers. More specifically, we tested orientation scenarios 5 and 6 (scenarios 1 through 4 were not tested). To test the highest possible system temperature orientation (6), we placed the maximum sidelobes of both the transmit and receive horns roughly towards each other, as having the main beams of the two telescopes point directly at each other is not a physical possibility. This placed the GBT at 33.56° azimuth and 5.0° elevation and the 140-ft at 213.56° azimuth and 7.5° elevation.

Using the C-band receiver on the GBT to collect data, the transmitter was operated at a minimum power of 20mW while the power was peaked up by varying the GBT elevation from 5° to 15°. After settling on 6.6° elevation as the peak, we then swept in azimuth from 31° to 36°, settling on 33.6° azimuth as the peak. We repeated the peaking procedure for the 140-ft telescope, first varying elevation from 7.5° to 12.5° (it wasn't possible to go below 7.5° due to telescope limits), and settled on 7.5° elevation as the peak. We then moved in azimuth from 211° to 216°, and settled on 214.2° as the peak. Following this peaking procedure, the worst-case positions for scenario 6 was determined experimentally to be:

	Azimuth	Elevation
GBT	33.6°	6.6°
140-ft	214.2°	7.5°

With both telescopes in this worst-case orientation, and with the maximum attenuation levels set in the GBT IF rack (31dB), we intended to increase the transmitter power stepwise while reading the power from the optical link via a spectrum analyzer. However, the IF power monitor reached saturation at the lowest possible power setting of 20 mW, occurring well before the full power of 2.5W was transmitted, and so the experiment was discontinued. Although this saturation of the IF power monitor does not prove that the first amplifier is in compression, it does show that the C-band receiver cannot be used for astronomy observations during RadioAstron uplinks in this worst-case orientation.

We next repeated the experiment with the GBT pointed 180° from the worst-case azimuth, i.e., an example of orientation scenario 5, where the sidelobes of the 140-ft is seen by an isotropic GBT. Unlike the latter experiment, it was possible to increase the transmit power stepwise to 2.5W without saturating the GBT IF power monitor using maximum attenuation settings in the IF rack. However, when switching to IF rack attenuation levels typically used during astronomy observations (~20dB), the GBT IF power monitor saturated, suggesting that the C-band receiver is unusable for typical observations in this scenario as well.

The IF filter in the IF rack was next set to 5360-6640 MHz, which blocked the signal from the IF rack. When we turned on the transmitter, we saw the power in the IF rack power monitor increase by a small amount, indicating that either some of the signal was still bleeding through the filter skirts, or the LNAs were in compression, resulting in intermodulation products in the passband. It was not possible to determine with certainty if the LNAs were going into compression, so it may still be feasible to observe with the C-band receiver in its fully equipped configuration with internal mixers and filters if the LNAs do not compress.

After performing the C-band tests we switched to the GBT's X-band receiver. Maintaining orientations of both telescopes, with the GBT pointed 180° in azimuth from the 140-ft, the transmit power was increased to its maximum. No change in power level was apparent on the power monitor. We then returned the GBT to the previously determined worst-case position (33.6° azimuth and 6.6° elevation), and using both the wide and narrow band filters, still saw no effect when power levels were increased.

Based on these initial tests, we conclude that C-band observations should not be scheduled on the GBT during RadioAstron uplinks. If the maser on the RadioAstron satellite malfunctions, necessitating regular use of the transmitter, C-band observations could be made possible through the installation of a notch filter before the first amplifier of the C-band receiver, or by possibly covering the radome with a dichroic plate built to notch the uplink frequency. X-band observations appear to not be adversely affected by the RadioAstron uplink.

On Friday, August 14, 2015, we performed a test using the GBT's Ku-band receiver to determine the effect of the 7.2075 GHz RadioAstron uplink transmitter on it. The concern was whether the 1st harmonic of the transmitted signal would be detected at 14.4150 GHz. We began with the GBT and the 140-ft at the worst-case positions for orientation scenario 6, with an uplink power of 2W. No signal was detected. We then transmitted a 14.4150 GHz CW signal from the Jansky Lab at a power of +12dBm (.016 W) through a ridged guide horn pointed in the direction of the GBT. This signal was immediately apparent in the GBT Ku receiver passband (Figure 1).

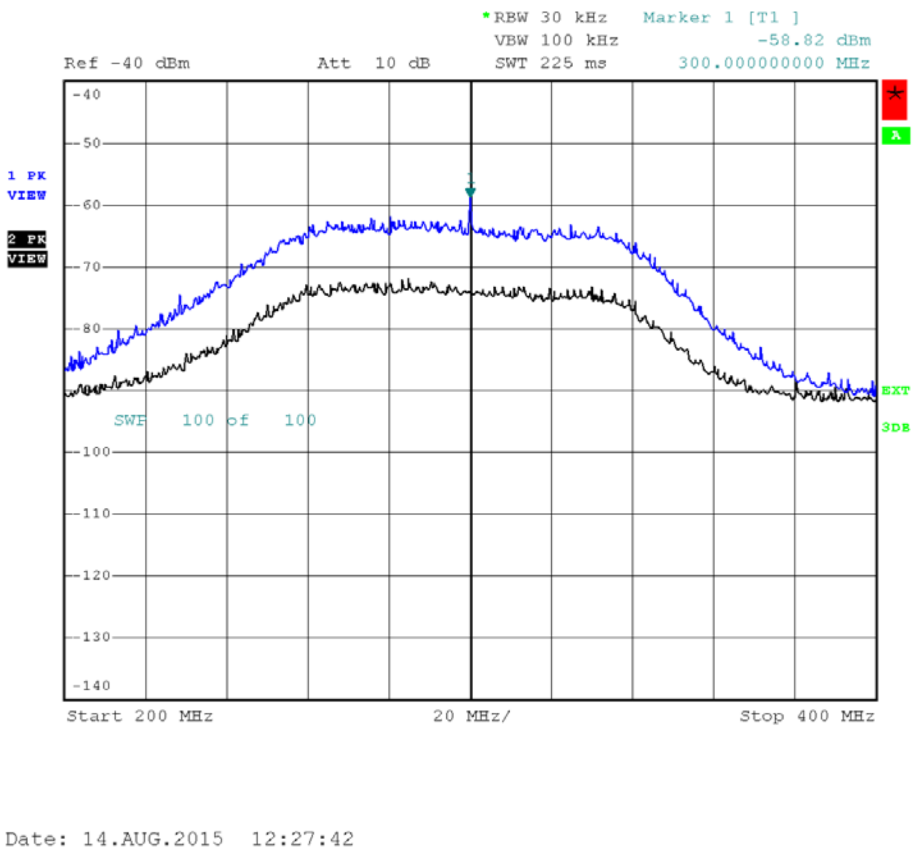

Figure 1: Test signal on (blue) and off (black) in the GBT Ku passband; GBT AZ 33.6° EL 6.6°. 10 dB attenuation was added to separate the two traces. The RadioAstron 7.2075 GHz uplink was transmitting 2 Watts during both tests and was not detected in the passband.

From the difference between the passband noise level and the received signal, plus the difference between the power of the test signal and that of the RadioAstron uplink, we can conclude that the first harmonic of the uplink is at least 34 dB down from the fundamental, and possibly much more. The azimuth of the GBT was next moved from 33.6° to 123.6° while looking for the RadioAstron harmonic, which was still not seen.

Brief Radiation Safety Assessment

The current recommended limit of RF exposure for the general public at 7.2075 GHz is 1 mW cm^{-2} (see below table from OET Bulletin 56, August 1999). By simply accounting for the illumination of the dish with a transmit power of 2.5W, we determine a power density of 0.18 mW cm^{-2}, neglecting any space loss. Given this power density, the RadioAstron transmitter on the 140-ft is well below the recommended exposure limits for the general public. The unlikelihood that human exposure would occur in the main beam of the telescope, but rather through sidelobe exposure, further decreases the safety risks.

Table 1. ***FCC Limits for Maximum Permissible Exposure (MPE)***

(A) Limits for Occupational/Controlled Exposure

Frequency Range (MHz)	Electric Field Strength (E) (V/m)	Magnetic Field Strength (H) (A/m)	Power Density (S) (mW/cm^2)	Averaging Time $\|E\|^2$, $\|H\|^2$ or S (minutes)
0.3-3.0	614	1.63	(100)*	6
3.0-30	1842/f	4.89/f	$(900/f^2)$*	6
30-300	61.4	0.163	1.0	6
300-1500	--	--	f/300	6
1500-100,000	--	--	5	6

(B) Limits for General Population/Uncontrolled Exposure

Frequency Range (MHz)	Electric Field Strength (E) (V/m)	Magnetic Field Strength (H) (A/m)	Power Density (S) (mW/cm^2)	Averaging Time $\|E\|^2$, $\|H\|^2$ or S (minutes)
0.3-1.34	614	1.63	(100)*	30
1.34-30	824/f	2.19/f	$(180/f^2)$*	30
30-300	27.5	0.073	0.2	30
300-1500	--	--	f/1500	30
1500-100,000	--	--	1.0	30

f = frequency in MHz *Plane-wave equivalent power density

NOTE 1: Occupational/controlled limits apply in situations in which persons are exposed as a consequence of their employment provided those persons are fully aware of the potential for exposure and can exercise control over their exposure. Limits for occupational/controlled exposure also apply in situations when an individual is transient through a location where occupational/controlled limits apply provided he or she is made aware of the potential for exposure.

NOTE 2: General population/uncontrolled exposures apply in situations in which the general public may be exposed, or in which persons that are exposed as a consequence of their employment may not be fully aware of the potential for exposure or can not exercise control over their exposure.