Notes on columns in above table:

Fig: The figure number in this document, from which the data in each row of the table were derived.

Radar: A description of the specific automotive radar. "Cont." means the radar provided by the Continental Corporation, and "Bosch" by Robert Bosch GmbH. "200" means a nominal bandwidth of 200 MHz (in fact 170 MHz) and "WB" means the wideband radar with a nominal bandwidth of 800 MHz (Continental) or 1550 MHz (Bosch).

Tb(peak) K: The antenna temperature in degrees K measured for the peak of emission found at 79.1 GHZ, as seen within a 2-MHz filter channel. This is for reference, but is not used in the subsequent calculations.

Tb(plateau) K: The antenna temperature in degrees K measured for the plateau of emission, excluding any isolated peaks, as seen within 2-MHz filter channels. The remaining columns in this table are based on this plateau of emission, not on the stronger peak at 79.1 GHz.

Prx: The power received, dBm. Calculated from Tb plateau .k. B, with k Boltzman's constant = $1.38.10^{-23}$, and B the bandwidth in Hz. For "Cont 200" the bandwidth is 170 MHz, for Bosch WB 1550 MHz, and for Cont.WB 800 MHz.

Meas. Range km: The line-of-sight distance, in km, between the automotive radar and the receiver used for these measurements.

Free space loss dB: This is the attenuation introduced by the free-space Range (km) given in the adjacent column, for isotropic transmit and receive antennas. This is calculated from $20.\log(4.\pi.d/\lambda)$, with d the distance in meters and λ the wavelength in meters, and does not include atmospheric attenuation.

Atm. Atten dB: This is the computed additional attenuation introduced by the atmosphere at this frequency, for the corresponding line-of-sight distance given in the "Range" column. A value of 0.15 dB/km is taken.

Pfd dBW/m^2 : This is the power flux density, integrated over the assumed transmitter bandwidth, of the total emission from the respective radar, at the receiver. Units dBW/m^2. This includes *only the plateau of emission,* not any isolated spikes within the spectrum. The receiver antenna gain of 35.8 dBi is taken into account in this calculation.

Spfd dBW/m^2/MHz: The spectral power flux density at the receiver, in units of dBW/m^2/MHz. This is derived from the previous column using (where possible) the measured bandwidth of emission, or by an assumed transmitter bandwidth.

The last line of the table gives the threshold spfd for interference taken from Table 2 in ITU-R RA.769-2, converting from "per Hz" into "per MHz" units.

EIRP: The derived effective isotropic radiated power (EIRP) at the transmitter, based on the received pfd shown in a previous column. Units of dBm. This is calculated from
EIRP = power_received + path loss + atmos.loss – recv_ant_gain, with
power_received from column 5 of this table,
path_loss from column 7,
atmos.loss from column 8,
and with *recv_ant_gain* = 35.8 dBi.

Avoidance Zone radius: Obtained by scaling the 1.7-km or the 26.9-km measurements to give the minimum distance from the radio telescope that would be necessary for a single transmitter, mounted on a single vehicle, to give a level of interference at or below the threshold specified in ITU-R RA.769, which is defined for a 0 dBi receiving antenna gain. In calculating the avoidance zone radius, an atmospheric attenuation of 0.15dB/km has been added to the normal free space inverse square distance path loss. This distance is then calculated from the difference between the observed spfd (column 10, Table 1) and the RA.769 value for spfd (last row, column 10), with the corresponding distance corresponding to this differential loss taken from Figure 9.
This is included purely for illustrative purposes. For multiple transmitters on a given vehicle, and for more than one vehicle in view of the telescope, the avoidance zone radius would be correspondingly increased. Mitigation factors such as any terrain shielding, orientation of the transmitter antenna with respect to the observatory, or attenuation of the transmitter if mounted behind the vehicle bumper have not been taken into account, and would tend to reduce the avoidance radius.

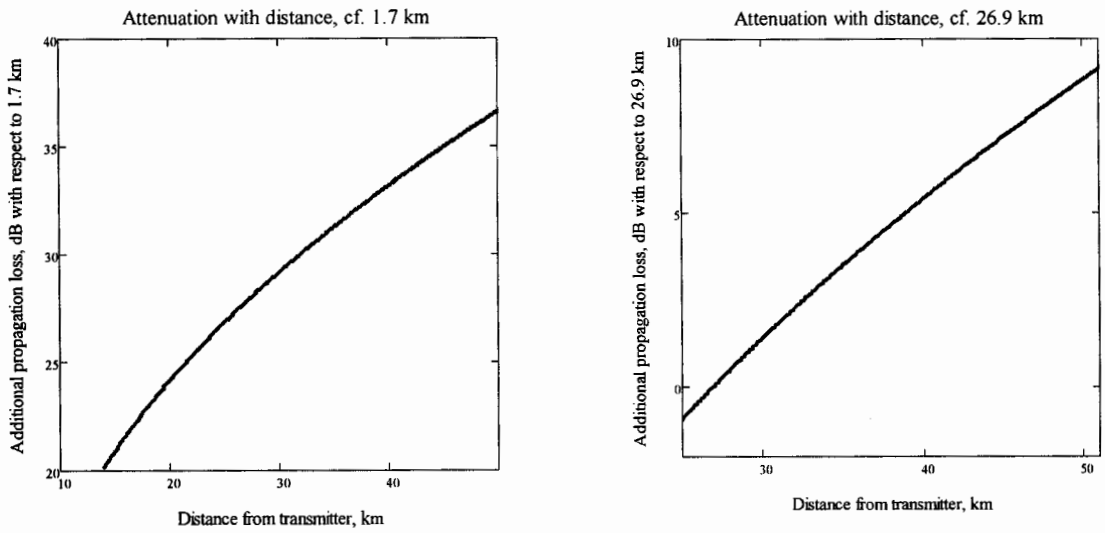

Figure 9 The extra propagation loss vs. distance, compared to a distance of 1.7 km (left) or 26.9 km (right), including both inverse square of distance free space loss and 0.15 dB/km of atmospheric attenuation.

8 Comparison with ITU-R RA.769.

The measured values of Table 1 above can be compared to the threshold interference levels defined in ITU-R RA.769. That recommendation contains separate recommendations for the case of broadband interference (Table 1 of RA.769, "continuum"), or for narrow-band (Table 2 of RA.769,"spectral line") interference. In the current context, allowing for the dilution of the 170-MHz or 1550-MHz bandwidth of the interfering transmitter signal over the 8 GHz receiver bandwidth as defined in RA.769, the different interference thresholds are within a few dB of each other.

8.1 Spectral Line Threshold

First we consider the spectral line case. Table 2 of ITU-R RA.769-2 gives a threshold level of interference detrimental to radio astronomy spectral-line observations in this frequency band of -208 dBW/m^2/Hz, equivalent to -148 dBW/m^2/MHz. As seen in Table 1 above, by chance most of the measurements described here give an spfd at a distance of 26.9 km within a few dB of this limit. The rightmost column of Table 1 above gives the necessary avoidance zone radius in order that the corresponding transmitter measured here does not produce an interference level at the radio telescope in excess of the spectral line threshold defined in RA.769. Note this is purely for illustrative purposes, and applies to a single transmitter on a single vehicle.

8.2 Continuum Threshold

The corresponding continuum spfd threshold interference level, taken from ITU-R RA.769-2 Table 1, is -228 dBW/m^2/Hz, equivalent to -168 dBW/m^2/MHz. This is 20 dB more stringent than the spectral line case discussed above. However, the interfering emission in this case must be averaged over 8 GHz. For example, if emission from a single Continental 170-MHz bandwidth radar were diluted over 8 GHz, the average spfd per MHz would be reduced by 8000/170 = 16.7 dB, which by chance is close to the 20 dB greater stringency of continuum interference threshold.

Note that, if there are several transmitters on a given vehicle *on different frequencies*, then although the spectral line threshold spfd (in any 1 MHz band) may remain unchanged, nevertheless the average spfd within an 8-GHz band, as defined by the RA.769 continuum threshold, would increase correspondingly. Table 2 below summarizes the comparison between our measurements and the threshold for interference to continuum observations defined in RA.769-2.

Table 2 Comparison of Measurements with RA.769 Continuum Threshold

Fig	Radar	Tb plateau K	Meas. Range km	Atm. Atten dB	Transmitted bandwidth MHz	Spfd, diluted over 8 GHz band dBW/m^2/MHz	Avoidance Zone radius km
4	Cont.200 Stationary	968	1.7	0.3	170	-131.8	48
5	Bosch.WB Stationary	60.1	1.7	0.3	1550	-134.3	41
6	Cont.200 Stationary	0.68	26.9	4.0	170	-163.4	38
7	Cont.200 In motion	1.07	26.9	4.0	170	-161.4	43
8	Cont.WB In motion	0.41	26.9	4.0	800	-158.9	51
-	**RA.769 8 GHz bw continuum threshold**	-	-	-		**-168**	-

Table 2 Comparison of the measurements with the spfd threshold of interference for continuum observations, as defined in Table 1 of RA.769-2

Notes on columns in above table:

Fig: The figure number in this document, from which the data in each row of the table were derived. Same as Table 1.

Radar: A description of the specific automotive radar. "Cont." means the radar provided by the Continental Corporation, and "Bosch" by Robert Bosch GmbH. "200" means a nominal bandwidth of 200 MHz (in fact 170 MHz) and "WB" means the wideband radar with a nominal bandwidth of 800 MHz (Continental) or 1550 MHz (Bosch). Same as Table 1.

Tb(plateau) K: The antenna temperature in degrees K measured for the plateau of emission, excluding any isolated peaks, as seen within 2-MHz filter channels. The remaining columns in this table are based on this plateau of emission, not on the stronger peak at 79.1 GHz. Same as Table 1.

Meas. Range km: The line-of-sight distance, in km, between the automotive radar and the receiver used for these measurements. Same as Table 1.

Atm. Atten dB: This is the computed additional attenuation introduced by the atmosphere at this frequency, for the corresponding line-of-sight distance given in the "Range" column. A value of 0.15 dB/km is taken. Same as Table 1.

Transmitted bandwidth: This is the actual bandwidth occupied by the emissions from each transmitter. For multiple transmitters on different frequencies, this figure would have to be correspondingly increased.

Spfd, diluted over 8 GHz band: This is derived from the column **Spfd** in Table 1, but allowing for the dilution of the transmitted signal over the 8 GHz receiving band defined by RA.769. An amount *10.log(B/8000)* is added to the values tabulated under **Spfd** in Table 1, with B corresponding to the bandwidth of the radar emission in MHz, given in column 6. The last row in this table contains the spfd threshold of -228 dBW/m^2/Hz taken from Table 1 of RA.769-2, equivalent to 168 dBW/m^2/MHz.

Avoidance Zone radius: Exactly as in Table 1, but for the RA.769 continuum threshold. This distance is calculated from the difference between the observed spfd given in column 7, **Spfd diluted over 8 GHz**, and the RA.769 value for continuum spfd threshold (last row, column 7), with the distances corresponding to this differential loss derived as before from Figure 9.
As with Table 1, this is included purely for illustrative purposes. For multiple transmitters on a given vehicle, and for more than one vehicle in view of the telescope, the avoidance zone radius would be correspondingly increased. Mitigation factors such as any terrain shielding, orientation of the transmitter antenna with respect to the observatory, or attenuation of the transmitter if mounted behind the vehicle bumper have not been taken into account, and would tend to reduce the avoidance radius.

9 Estimated errors

Most of the received spectra were taken with the radar at a height of 1.6m at a fixed location. Tests made with the vehicle moving over a paved surface in Sells resulted in an increase in signal strength of about 2 dB. This change was most likely the result of a change in the ground reflection which interferes with the signal via the direct path. For example, a ground reflection coefficient magnitude of 0.3 (-10 dB) results in a variation of about +/- 2 dB depending on the reflection phase, which depends on the height of the radar and the elevation angle of the line of sight to the receiver. Uncertainty in the

atmospheric attenuation is another source of error. The 225 GHz "tipper" radiometer at the 12-M telescope was used to derive a zenith precipitable water vapor content of 4.3mm, which corresponds to 11% relative humidity at 300K. Using the curves of Shambayati the attenuation at 79 GHz is estimated to be 0.1 dB/km for the water vapor and 0.04 dB/km for the dry atmosphere for a total of 4 dB for the 26.9 km path. The uncertainty in this estimate is about +/- 1 dB. Using the ITU-R P.620 recommendation, for a high dry site the total atmospheric attenuation would be about 0.135 dB/km, in good agreement with Shambavati. Another estimate was obtained by measuring the contribution of the atmosphere to the receiver noise. At an elevation of 3 degrees the atmosphere contributed 100K which corresponds to 4.8 dB of attenuation. If we assume a scale height for the water of 2 km then the path length at 3 degrees is 38 km, so that the loss for a horizontal path of 26.9 km is estimated by this alternate method to be 3.5 dB.

The estimates of EIRP made at different distances are in quite good agreement. With the vehicle stationary, the estimated EIRP from 26.9 km of the plateau of emission from the Continental, 200-MHz radar is 9.2 dBm; however, the comparison with results when the vehicle were in motion suggest that this value may be artificially low, presumably because of ground reflections. With the vehicle in motion at 27 km, 11.2 dBm was derived. See Figure 6 and Figure 7. At 1.7 km, the corresponding estimate (Figure 4) is 13.0 dBm, some 1.8 dB greater. This difference of 1.8 dB might be attributable to an underestimate of atmospheric attenuation over the 27 km path, to different reflections from the road and nearby terrain, or to differences in orientation of the transmitter antenna with respect to the receiver at Kitt Peak. The elevation angle towards the Kitt Peak receiver from the 1.7 km distant site was approximately -6 degrees, while from the Sells airport was approximately +10 degrees. The spfd derived here from the measurements at a distance of 1.7 km of the Continental (170 MHz) radar was -9.3 dBm/MHz, while the manufacturer measured -9.0 dBm/MHz. Considering the possible sources of error, the agreement with the manufacturer's data, and between the different measurements at different distances reported here, is considered to be very good.

10 Conclusions

Tests performed with short range vehicular radar systems, operated at distances of 1.7km and 26.9 km from the University of Arizona's 12 Meter millimeter wave telescope, demonstrated that these radars could have a significant impact upon radio astronomy observations in the 77 to 81 GHz region. A zone of avoidance of about 30 to 40 km around a mm-wave observatory would be needed, in order to keep interference from a single vehicle below the threshold defined in RA.769-2. Smaller zones of avoidance might suffice in areas without direct line of sight to the radio telescope and/or by taking some of the above mentioned mitigation factors into account. ITU-R RA.1272-1 specifically recommends that such zones be established around mm-wave astronomical observatories, following the procedure outlined in Recommendation ITU-R RA.1031-2.

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