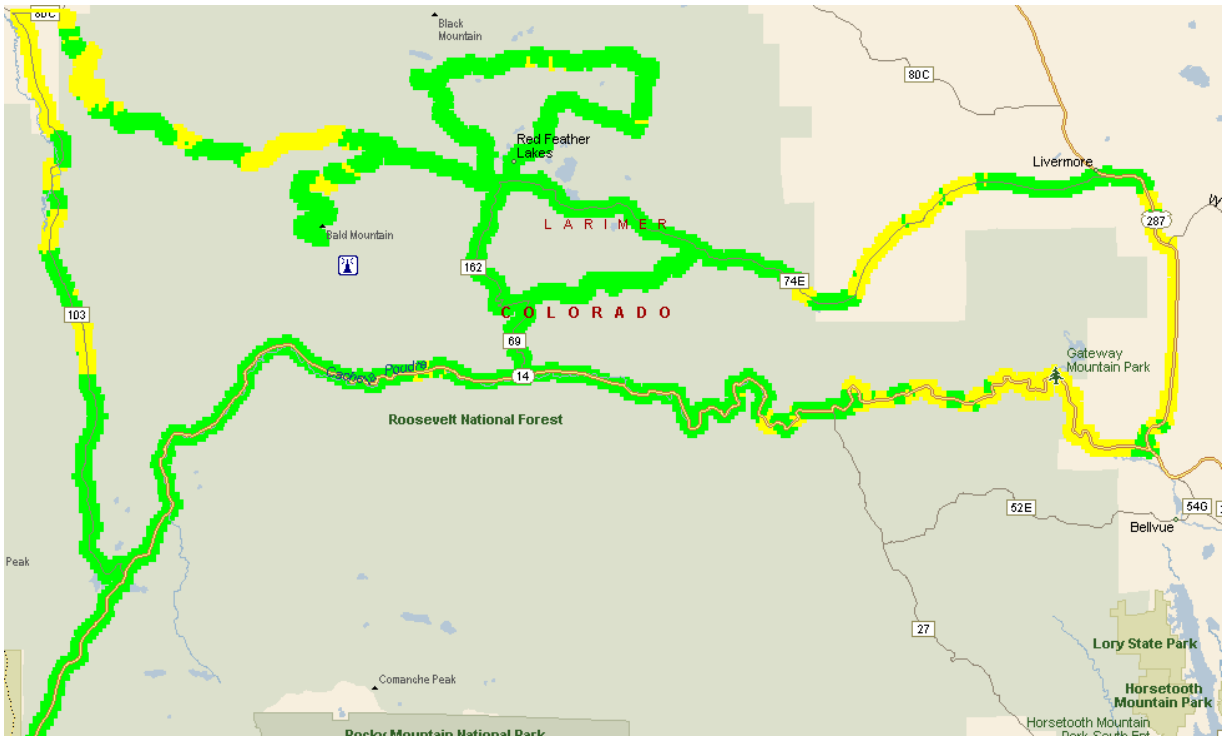
VHF & 800 MHz Measured Radio Coverage From Middle & South Bald Mountains



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1.0 Executive Summary

The principal land mobile radio system for Larimer County first responders is the 800 MHz State of Colorado Digital Trunked Radio System (DTRS). The County also operates a legacy VHF radio system (150-174 MHz). VHF radio coverage and 800 MHz radio coverage are poor or nonexistent in the mountainous northwest part of the County, including the Cache La Poudre River canyon (CO 14), Red Feather Lakes, Crystal Lakes, Glacier Meadows, and recreational areas in the Roosevelt National Forest. This lack of radio coverage also affects other public safety users, including the U.S. Forest Service, FBI, Larimer County Search and Rescue, and the Colorado State Patrol.

Larimer County has been working for several years to establish a radio site to correct these coverage shortfalls. Computer propagation models show that either Middle Bald or South Bald Mountain should greatly improve coverage in the problem areas, but drive test measurements are generally more accurate than computer models and the County desired the best information possible before pursuing site development further. In September of 2009, Larimer County retained Pericle Communications Company, a consulting engineer firm, to conduct a drive test survey to measure both VHF and 800 MHz radio coverage from Middle Bald and South Bald Mountains.

To measure radio coverage, Pericle conducted a drive test survey in accordance with TIA TSB-88-C, an industry standard [5]. The test signals for the survey consisted of test transmitters temporarily installed at Middle Bald and South Bald and existing control channel signals from six DTRS sites in the County. After Larimer County secured a special use permit from the U.S. Forest Service, Pericle installed one VHF and one 800 MHz transmitter on each mountain peak. Over 5,000 measurements were collected on each of the 10 frequencies corresponding to the four test transmitters and six DTRS sites. The particular drive routes driven during the study were specified by Larimer County and they include, but are not limited to, Larimer County Road 74E from U.S. 287 to Red Feather Lakes, County Road 103 from CO 14 to Four Corners, and CO 14 from Cameron Pass to U.S. 287. The company exercised extreme care to leave little or no trace of the transmitter installations after they were removed at the end of the survey on October 3, 2009.

Figure 1 shows the measured VHF coverage from South Bald Mountain using the following legend for radio carrier amplitude, C: $C < -106$ dBm = Red, -106 dBm $\leq C < -80$ dBm = Yellow, $C \geq -80$ dBm = Green. A signal level of -106 dBm represents the service threshold for a Project 25 compliant digital radio operating from a moving vehicle. The second threshold of -80 dBm is for informational purposes only and represents those areas where a significant margin exists to aid indoor coverage. Figure 2 shows existing 800 MHz coverage from the six DTRS sites in the County.

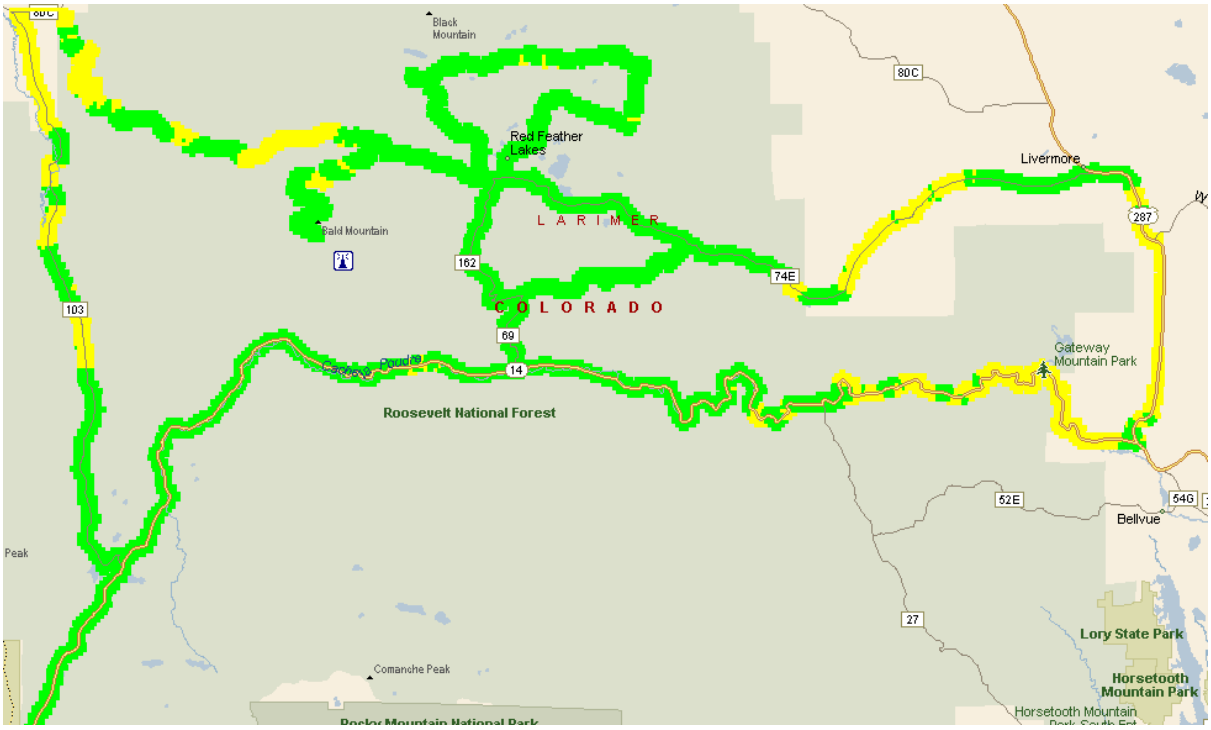

Figure 1 - VHF Mobile Outbound Coverage from South Bald Mountain

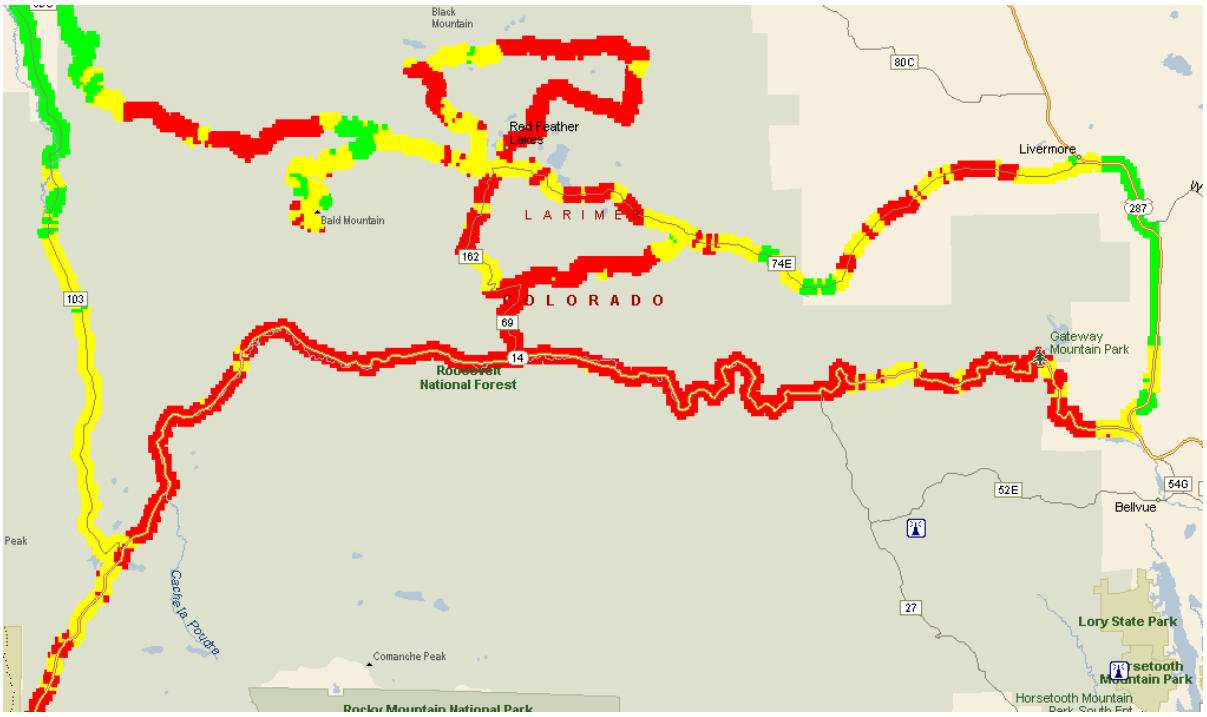

Figure 2 - 800 MHz Mobile Outbound Coverage from Existing DTRS Sites

Note from Figure 2 that there are significant 800 MHz coverage gaps (red tiles) over most of the desired coverage area using the existing network.[1] In Figure 3, we see that South Bald Mountain fills in most of these 800 MHz coverage gaps.

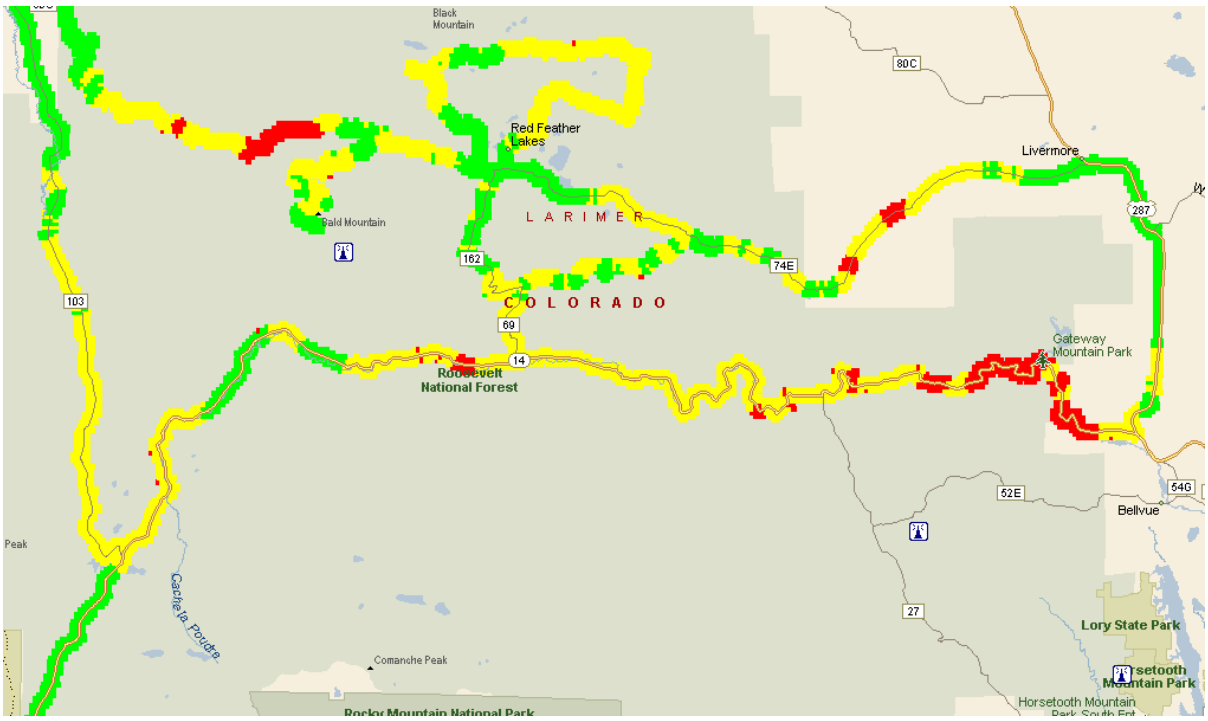

Figure 3 - 800 MHz Mobile Outbound Coverage from South Bald Plus DTRS

To quantify coverage, Pericle computed the Service Area Reliability (SAR) from the measured data. The SAR is the ratio of uniformly distributed grid points, also called tiles, with measured values above the service threshold to the total number of tiles measured. Table 1 lists the SAR values from the drive test survey for mobile radio outbound coverage (repeater site to vehicle).

Table 1 - Service Area Reliability for Mobile Outbound
(Gridded to 5,663 200m square tiles to remove spatial bias)

Site and Frequency Band	-106 dBm	-80 dBm
Middle Bald VHF	99.3%	67.6%
South Bald VHF	100%	74.7%
Middle Bald 800 MHz	78.1%	12.3%
South Bald 800 MHz	83.6%	20.5%
Six Existing DTRS Sites	48.2%	14.0%
Middle Bald 800 MHz + Six DTRS Sites	87.9%	26.1%
South Bald 800 MHz + Six DTRS Sites	91.3%	34.0%

[1]Both yellow and green tiles indicate adequate signal levels. Only red tiles indicate signal levels below the service threshold.

From Table 1, we see that South Bald Mountain performs noticeably better than Middle Bald Mountain at both VHF and 800 MHz frequencies. At VHF, South Bald provides 100% coverage over the County-specified drive route. At 800 MHz, South Bald improves 800 MHz coverage from the existing DTRS sites from just 48.2% to 91.3%.

Mobile inbound coverage (vehicle to repeater site) is estimated by scaling the outbound measurements to account for differences in transmitter power and receiver sensitivity. For mobile inbound, the estimated scale factor is 1 (0 dB), so the mobile outbound performance in Table 1 is also the best estimate of mobile inbound performance.[2]

2.0 Test Methods and Approach

This study was conducted from September 21, through October 3, 2009 by Mr. Jay Jacobsmeyer (*Pericle*), Mr. Brian Singer (*Pericle*), and Mr. Mike Ray (*Pericle*) with assistance from Mr. David Rowe (*Larimer County*) and Mr. Steve Schneider (*Larimer County*). The topography of the area to be tested is shown in Figure 4. Note that the Cache La Poudre River canyon has especially steep walls, making it difficult to provide radio coverage unless the repeater site is close to and above the canyon.

Figure 4 - Larimer County Topography in Study Area

[2]The reader is cautioned against attributing too much precision to this scale factor as it will vary depending on the specific parameters of the system that is actually constructed.

Table 2 lists the site coordinates and test frequencies used for each site measured in the drive test survey. The test frequencies at the DTRS sites were the active control channels in use at the time of the survey (control channels transmit continuously). The test frequencies for Middle and South Bald Mountains were provided by Larimer County and were programmed in the test transmitters by Mr. Singer.

Table 2 - Site & Frequency Data for Drive Test Survey

Site	Latitude (N, NAD 83)	Longitude (W, NAD 83)	Frequency (MHz)
Middle Bald Mountain (10,998')	40-45-56.5	105-42-27.0	159.1500 MHz 852.5125 MHz
South Bald Mountain (11,004')	40-45-09.0	105-41-44.0	155.6700 MHz 851.5125 MHz
Bull DTRS Site	40-56-50	105-55-31	852.5875 MHz
Bear Gulch DTRS Site	40-52-37	105-41-46	852.7500 MHz
Buckhorn Mountain	40-37-05	105-19-37	853.2625 MHz
Bald Mountain North	40-21-21	105-15-47	853.6750 MHz
Prospect Mountain	40-12-39	105-31-13	853.8250 MHz
Horsetooth Mountain	40-32-49	105-11-52	853.8875 MHz

There are no roads to the top of either Middle Bald or South Bald Mountain, so it was necessary to use All Terrain Vehicles (ATVs) with a small trailer to carry the transmitters, gasoline generators, antennas, coaxial cable, and related hardware needed to operate the test sites for the duration of the project. The bulk of the labor required for this project involved the installation and removal of the test transmitters on the two peaks. The actual collection of measurements required a much smaller effort in comparison.

The first opportunity to install the test transmitters was the day the USFS special use permit was issued, on September 21, 2009. Pericle attempted to do the Middle Bald installation on that date, but heavy snow above 10,000' elevation on the 21st and 22nd precluded any installation work that week. Instead, Mr. Rowe led a site survey (on foot) of each site to better prepare Pericle personnel for the installation the following week.

Installation on Middle and South Bald occurred on September 28, and 29, 2009, respectively. Figures 5-8 show various stages of installation at each of the two peaks. Some preliminary measurements were collected the evening of Tuesday, September 29th. Bad weather moved into the area early Wednesday morning bringing 70 mph winds and snow. The weather damaged the antenna mount at South Bald and shredded the tarpaulin that protected the electronic equipment from moisture. This damage created additional work on Wednesday and Thursday to repair the damage and relocate the equipment and trailer to a more protected location on the peak. Measurements were completed for South Bald on Friday, October 2nd, but an repeater failure on Middle Bald required a second pass through the drive route starting at midday on Saturday, October 3rd. The South Bald site was torn down in the morning.

Figure 5 - Test Transmitter System for Middle Bald (South Bald Similar)
(Generator, Auxiliary Fuel Tank, VHF & 800 MHz Repeaters)

Figure 6 - Equipment Loaded on ATV and Trailer

Figure 7 - Equipment Parked Just Below Peak of Middle Bald

Figure 8 - Equipment Installation on South Bald (Middle Bald Similar)

The drive test survey was completed and all equipment was brought down from both peaks by 1730 on Saturday, October 3rd.

Measurements were collected by two computer-controlled receivers:

- Grayson WMS 800 MHz receiver, S/N 237018 (8 frequencies)
- Grayson WMS VHF receiver, S/N 280091 (2 frequencies)

Each receiver was connected to a 3 dBd magnetic mount antenna on the rooftop of the test vehicle, a late model six-passenger Dodge pickup truck. The coaxial cable loss between each antenna and corresponding test receiver closely approximates the loss expected in a typical vehicle installation. The receiver noise floor of each instrument is about -126 dBm which is well below the user radio service threshold of -106 dBm, so the test receiver sensitivity does not impair the accuracy of the survey measurements.

The objective of the measurements survey is to measure the mean signal level in the presence of multipath fading, the usual environment in land mobile radio. For a 90% confidence interval of +/- 1 dB in Rayleigh-distributed multipath fading, TSB-88-C requires that at least 50 subsamples be linearly averaged over at least 40 wavelengths of traveled distance.[3] The receiver software was configured in accordance with these parameters. the VHF and 800 MHz test transmitter technical data is listed in Tables 3 and 4, respectively. Cable loss and system return loss were measured using an Anritsu Model 332D Site Master Cable and Antenna Analyzer.

Table 3 - VHF Test Transmitter Technical Data

Parameter	Middle Bald	South Bald
Frequency	159.1500 MHz	155.6700 MHz
40 wavelengths	247’	253’
Transmitter Power	25 W	25 W
Transmitter Model	MTR2000 (T5544)	Quantar T5365A
Transmitter S/N	474CGP0334	225CXB0157
Coaxial Cable Insertion Loss	0.43 dB	0.94 dB
System Return Loss	21.0 dB	22.1 dB
Antenna Gain	0 dBd	0 dBd
Test ERP	22.7 W	20.1 W
Projected Operational ERP	282 W	282 W

[3]Averaging distance can vary with vehicle speed. Each Grayson receiver collects one subsample measurement every 10 ms. The VHF receiver was configured to scan two test frequencies plus two dummy frequencies (used to improve accuracy and speed). At 60 mph (88 fps), a distance of 176 feet is traveled before 50 subsamples are collected on each 150 MHz frequency, but 40 wavelengths at 155.67 MHz corresponds to 253 feet and the software continues to collect measurements until at least 50 subsamples are collected *and* at least 40 wavelengths are traveled. Therefore, each 150 MHz sample describes the average performance over a distance of 253 feet, regardless of vehicle speed. The 800 MHz receiver was configured to scan 8 frequencies. At 60 mph (88 fps), a distance of 352 feet is traveled before 50 800 MHz subsamples are collected on each frequency. Forty wavelengths at 851.2125 MHz corresponds to 46’, so each 800 MHz sample describes the average performance over a distance of between 46 and 352 feet, depending on vehicle speed.

Table 4 - 800 MHz Test Transmitter Technical Data		
Parameter	**Middle Bald**	**South Bald**
Frequency	852.5125 MHz	851.5125 MHz
40 wavelengths	46’	46’
Transmitter Power	50 W	50 W
Transmitter Model	MTR2000 (T5544A)	MTR2000 (T5544A)
Transmitter S/N[4]	593CAH002	593CAH002
Coaxial Cable Insertion Loss	1.5 dB	3.1 dB
System Return Loss	17.7 dB	13.5 dB
Antenna Gain	3 dBd	3 dBd
Test ERP	70.6 W	48.9 W
Projected Operational ERP	158.5 W	158.5 W

Geographical coordinates were generated and recorded automatically by a GPS receiver using a roof-mounted antenna. The Grayson receiver has a noise floor of -126 dBm and it can effectively reject adjacent channel and intermodulation interference to a level of -40 dBm.

The drive route was specified by Larimer County and is shown in Figure 9 along with the locations of the eight sites measured for this study.

Before creating digital coverage maps and calculating service area reliability (SAR), the data were gridded to a uniform grid with 200 meter square tiles to remove any spatial bias from the measurements. The gridding program interpolates all measurements within 400 meters of the center of the grid tile using an inverse distance-squared algorithm. If no measurements are found inside the search radius, no measured value is assigned to that grid point. Service area reliability is computed from only those grid points where measurements exist. Inaccessible grid points are not counted in the service area reliability.

Operational repeater sites typically operate at higher Effective Radiated Power (ERP) than test transmitters and for this reason, the collected measurements are scaled by the ratio of the projected ERP to the test ERP (see Tables 3 and 4).

Because measurements were taken from vehicles with rooftop antennas, the results represent mobile outbound (repeater site to user) coverage as opposed to portable coverage. Inbound mobile radio coverage and portable outbound and inbound radio coverage can be estimated from outbound mobile coverage using appropriate scale factors to reflect differences in gain and loss between the two types of radios and outbound versus inbound calls.

[4]After the 800 MHz repeater failure on Middle Bald Mountain, the South Bald repeater was moved to Middle Bald and the survey routes were d riven again. Thus, the final 800 MHz measurements for the two sites, taken on two different days, are from the same repeater.

Please see Appendix A for greater detail on the collection and analysis methods used for the drive test survey.

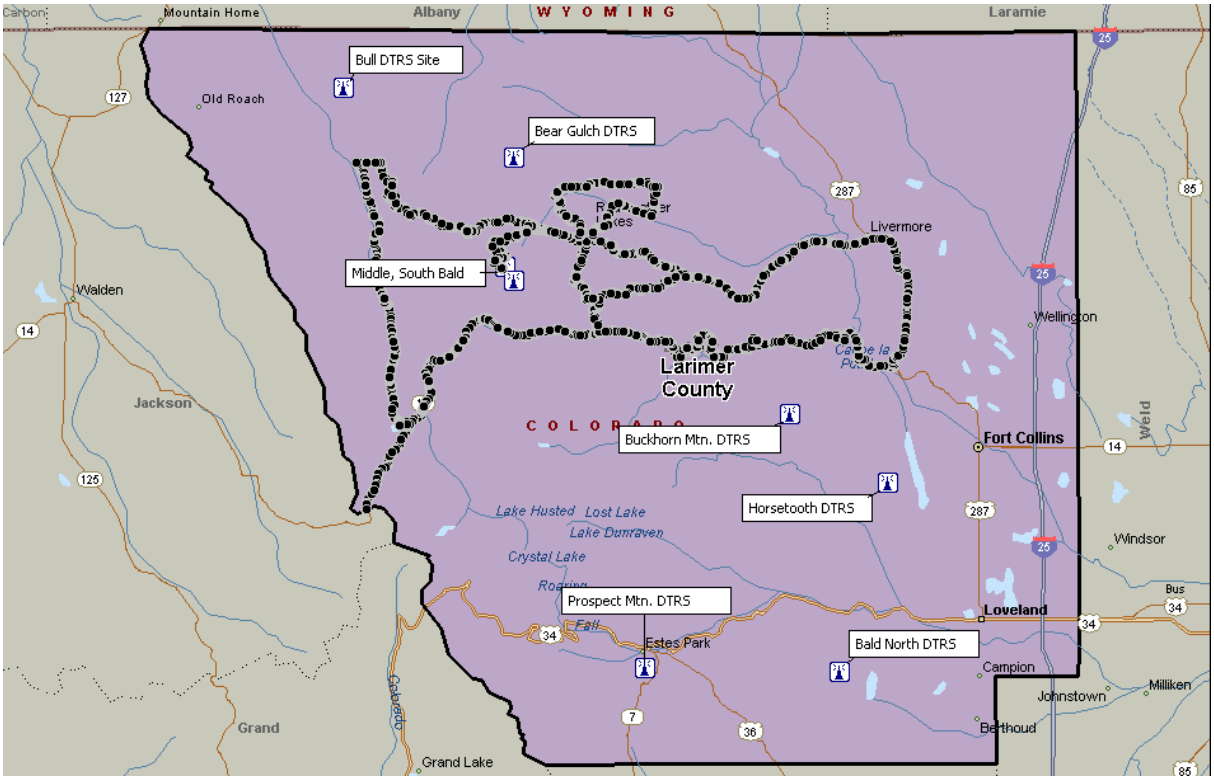

Figure 9 - Drive Route and Locations of Radio Sites

3.0 Results

Appendices B and C contains high resolution coverage maps for individual site coverage and composite coverage (800 MHz only). Unless noted otherwise, the following legend applies to the coverage maps in the appendices:

$C \geq$ -80 dBm	= Green
-106 dBm $\leq C <$ -80 dBm	= Yellow
$C <$ -106 dBm	= Red

The threshold of -106 dBm applies to a multipath fading channel which is the normal case for users who are moving and even stationary users if the environment around the user is changing (moving vehicles, moving personnel, etc.). Table 5 lists the sensitivity thresholds for Motorola XTL-5000 and XTS-5000 P25 radios. Note that the threshold in multipath fading depends on the desired Delivered Audio Quality (DAQ). Motorola recommends a value of -106 dBm (DAQ between 3.4 and 4.0) and this is the threshold used in this study. Project 25 compliant

radios from other manufacturers have similar performance. The second threshold of -80 dBm accounts for some building penetration loss.

Table 5 - Motorola Radio Service Thresholds
(12.5 kHz channel, C4FM, IMBE Vocoder)

Radio	Static (mfr. specs.)		Multipath Fading (per TSB-88-C)	
	5% BER (DAQ 2.0)	1% BER (DAQ 3.4)	2.0% BER (DAQ 3.4)	1.0% BER (DAQ 4.0)
XTL-5000 (Mobile)	-119.0 dBm	-117.4 dBm	-108.9 dBm	-105.4 dBm
XTS-5000 (Portable)	-119.0 dBm	-114.9 dBm	-108.9 dBm	-105.4 dBm

Table 6 summarizes the Service Area Reliability for each site and at each frequency band, for the existing six DTRS sites, and for the combination of either Middle Bald 800 MHz or South Bald 800 MHz with the six existing DTRS sites.

Table 6 - Service Area Reliability for Mobile Outbound
(Gridded to 5,663 200m square tiles to remove spatial bias)

Site and Frequency Band	-106 dBm	-80 dBm
Middle Bald VHF	99.3%	67.6%
South Bald VHF	100%	74.7%
Middle Bald 800 MHz	78.1%	12.3%
South Bald 800 MHz	83.6%	20.5%
Six Existing DTRS Sites	48.2%	14.0%
Middle Bald 800 MHz + Six DTRS Sites	87.9%	26.1%
South Bald 800 MHz + Six DTRS Sites	91.3%	34.0%

We see from Table 6 that South Bald Mountain provides noticeably better service at 800 MHz than Middle Bald, but both sites improve coverage significantly over the status quo. For a single repeater site, VHF coverage is considerably better than 800 MHz coverage, an expected result for mobile outbound service. Free space loss, diffraction loss and foliage loss are all lower at VHF. In fact, we compared the VHF signal and 800 MHz signal at each tile and found that the average difference between VHF and 800 MHz for the South Bald site is 22.2 dB in favor of VHF.

Because a prospective 800 MHz site at either Middle Bald or South Bald would be part of the DTRS network, the most relevant measure of 800 MHz coverage is the combined coverage of the existing six Larimer County DTRS sites (only four of which contribute to drive test area) and either of the prospective sites. In the case of South Bald, the prospective site increases coverage in the service area from 48.2% to 91.3%. A Best Server plot, indicating the strongest 800 MHz site at each tile, is shown in Figure 10. This plot is also found in Appendix C.

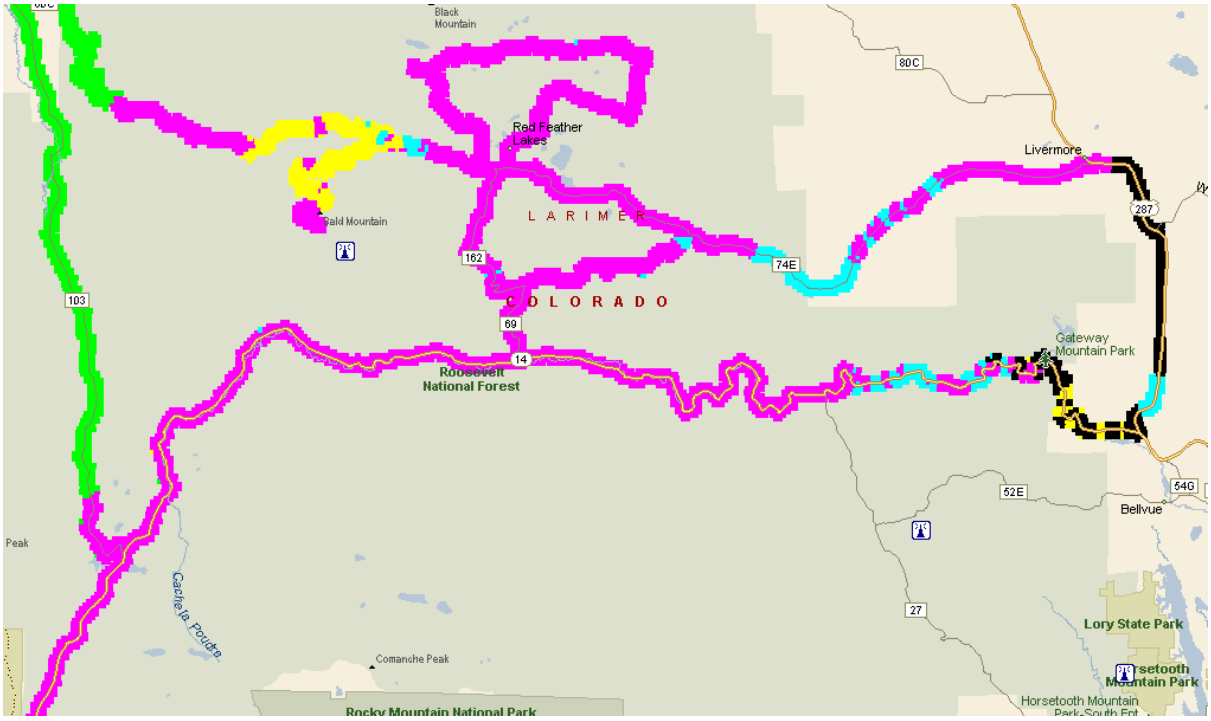

Figure 10 - South Bald 800 MHz Best Server Plot
(Legend: South Bald = Magenta, Bear Gulch = Yellow, Bull = Green, Buckhorn = Cyan, Horsetooth = Black)

4.0 Signal Level vs. Digital Voice Quality

This survey was limited to measuring signal strength which is a necessary, but not sufficient metric for ensuring adequate digital voice quality. When all land mobile radios were analog FM and all reputable manufacturers produced receivers with essentially the same DAQ for the same signal strength, it was not necessary to measure DAQ directly. With digital radio, the playing field is uneven. Some manufacturers do a better job of digital receiver design than others, especially with respect to mitigation of multipath delay spread. The bottom line: A high signal strength does not guarantee a high DAQ. If this project involved an acceptance test for a new radio system, we would recommend measuring audio quality directly, but the Larimer County VHF network and the DTRS are established networks and it is assumed that manufacturer problems, if any, have already been addressed. The risk lies in purchasing radios from a new vendor with no prior experience operating on either network.

5.0 Conclusions

A drive test survey was conducted to measure directly the VHF and 800 MHz land mobile radio coverage provided by Middle Bald and South Bald Mountains in Larimer County. The

drive test routes were specified by Larimer County and represent areas of known poor or non-existent radio coverage today. Drive test measurements show that a single VHF site at South Bald Mountain can provide nearly 100% mobile outbound service in the specified service area while an 800 MHz site at South Bald would increase the DTRS coverage from 48% to over 90%.

The conclusions regarding mobile outbound coverage assume a system that is properly maintained and free from radio interference at the repeater site or at the user radio. Systems with significant interference may work poorly even if the received signal is strong.

6.0 Cited References & Bibliography

[1] W.C. Jakes, ed., Microwave Mobile Communications, IEEE Press Reissue, 1994.

[2] W. C. Y. Lee, Mobile Cellular Telecommunications Systems, McGraw-Hill, 1989.

[3] S. M. Ross, A First Course in Probability, New York: MacMillan, 1984.

[4] R. J. Larsen, M. L. Marx, An Introduction to Mathematical Statistics and its Applications, Prentice-Hall, 1986, pp. 281.

[5] TIA TSB-88.1-C, "Wireless Communications Systems Performance in Noise and Interference Limited Situations, Part 1: Recommended Methods for Technology Independent Performance Modeling and Part 3: Performance Verification, February, 2008.

[6] C. Hill and T. Kneisel, "Portable Radio Antenna Performance in the 150, 450, 800, and 900 MHz Bands "Outside" and In-Vehicle," *IEEE Transactions on Vehicular Technology*, November, 1991.

[7] A. Davidson ad C. Hill, "Measurement of Building Penetration into Medium Buildings at 900 and 1500 MHz, *IEEE Transactions on Vehicular Technology*, February, 1997.

7.0 Acronyms

AWGN	Additive White Gaussian Noise
AM	Amplitude Modulation
AMPS	Advanced Mobile Phone System
APCO	Association of Public Safety Communications Officers
ARQ	Automatic Repeat-Request
BPSK	Binary Phase Shift Keying
CDMA	Code Division Multiple Access
CDPD	Cellular Digital Packet Data
DAQ	Delivered Audio Quality
dB	Decibels
dBi	Decibels relative to isotropic (for antenna gain)
dBd	Decibels relative to a half-wave dipole (for antenna gain)
dBm	Decibels relative to a milliwatt
DTR	Digital Trunked Radio
EDACS	Enhanced Digital Access Control System
EDGE	A high speed data service offered on GSM networks
EIRP	Effective Isotropic Radiated Power
EMS	Emergency Medical Services
ENBW	Equivalent Noise Bandwidth
ERP	Effective Radiated Power (relative to half-wave dipole)
ESMR	Enhanced Specialized Mobile Radio
ETSA	Emergency Telephone Service Authority
FCC	Federal Communications Commission
FM	Frequency Modulation
GHz	Gigahertz (10^9 cycles per second)
GPRS	Wireless data service on GSM networks; will be replaced by EDGE
GPS	Global Positioning System
GSM	Global System for Mobile Communications
iDEN	Proprietary Motorola airlink standard used by Nextel
ITAC	Interoperability Tactical Channel
LTR	Logic Trunked Radio (a trunking protocol)
MHz	Megahertz (10^6 cycles per second)
NAMPS	Narrowband AMPS
NLEC	National Law Enforcement Channel
NPSPAC	National Public Safety Planning Advisory Committee
PCS	Personal Communications Services
RF	Radio Frequency
SAR	Service Area Reliability
SMR	Specialized Mobile Radio
TDI	Time Delay Interference (in simulcast networks)

TDMA	Time Division Multiple Access
TIA/EIA	Telecommunications/Electronic Industries Association
3G	Third Generation Wireless
TTA	Tower-Top Amplifier
VHF	Very High Frequency (30 MHz to 300 MHz)
UHF	Ultra High Frequency (300 MHz to 3 GHz)
WiFi	Trade name for systems that comply with IEEE 802.11 standards
WMS	Wireless Measurement System

Appendix A - Methods for Drive Test Collection and Analysis

This appendix describes the methods used for collecting drive test measurements and analyzing the results.

A. Measuring Fading Signals

The mobile radio channel is rarely line-of-sight and the received signal is the sum of many reflected and diffracted signals. The term *multipath fading* is used to describe the time-varying amplitude and phase that characterize the composite signal at the receiver. These fluctuations are usually modeled as Rayleigh fading with Rayleigh-distributed amplitude and uniformly distributed phase [1]. Figure A.1 is a plot of amplitude versus time for a typical Rayleigh fading mobile radio channel.

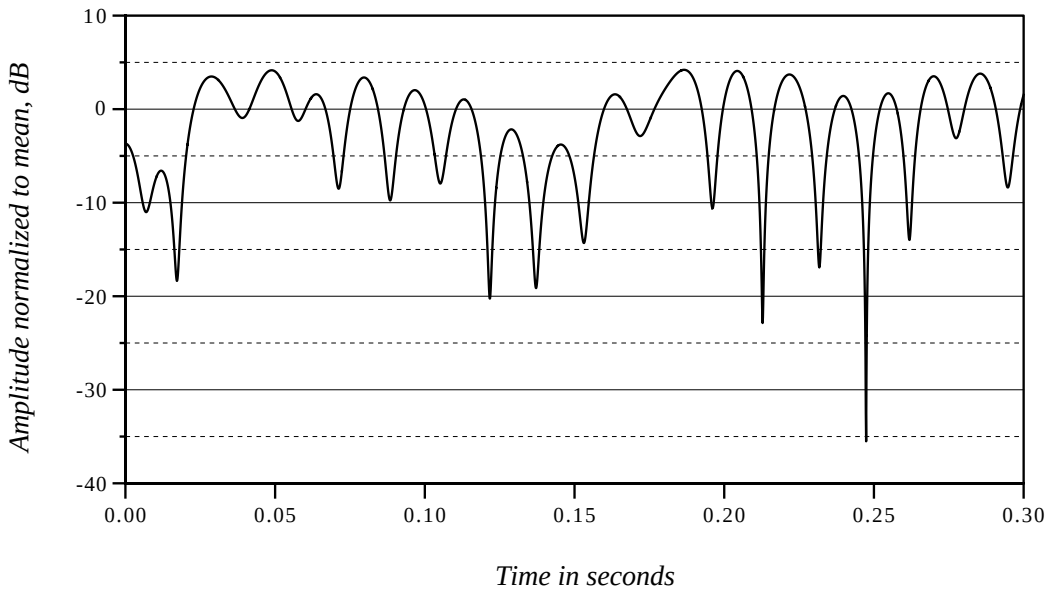

Figure A.1 - Time-Varying Amplitude on Rayleigh Fading Channel
(V = 30 mph, f_c = 850 MHz)

The local mean of the Rayleigh fading signal varies more slowly than the instantaneous amplitude and is commonly referred to as *shadow loss*. The most widely used statistical model of shadow loss assumes that the loss is log-normally distributed. In other words, if the signal level is given in decibel form (e.g., dBm), the received signal level, Y, has the normal probability density function,

$$f_Y(y) = \frac{1}{\sqrt{2\pi}\,\sigma}\, e^{-\frac{(y-\mu)^2}{2\sigma^2}} \tag{A.1}$$

where μ is the mean, and
σ is the standard deviation.

In mobile radio, the standard deviation of the signal amplitude is typically 8 dB for large service areas and 6 dB for small service areas [1], [2].

Mobile and portable receivers are usually specified to operate with a minimum local mean in the presence of Rayleigh fading. Thus, for the survey to be a useful indicator of receiver performance, we should estimate the local mean, *not* the instantaneous Rayleigh fading. Estimating the local mean requires that we average subsample measurements over some distance. The preferred distance is 40λ as it adequately smoothes the Rayleigh fading [2], [5]. Long distances tend to include changes in the local mean due to location variability and are therefore not desirable. However, there is no ironclad rule on the maximum averaging distance.

B. Number of Subsamples Required

A minimum number of subsamples is required to get an accurate estimate of the local mean within the 40 wavelength measurement distance (roughly 45 feet at 850 MHz). The 90% confidence interval for a Rayleigh fading signal is given by

$$\text{90\% Confidence Interval (dB)} = 20\ \text{Log}\left(1 + \left(\frac{1.65}{\sqrt{T_s}}\sqrt{\frac{4-\pi}{\pi}}\right)\right) \tag{A.2}$$

where T_S is the number of subsamples [2], [5]. Using (A.2), we find that a 90% confidence interval of +/- 1 dB requires at least 50 subsamples. See EIA TSB-88-C for a more complete treatment of this subject [5].[5]

C. Service Area Reliability

The service area reliability estimate is defined by the following expression:

$$\text{Service Area Reliability (\%)} = \frac{T_p}{T_t}\ 100\% \tag{A.3}$$

where T_p is the total number of grid points passed (e.g., those where C > -106 dBm), and

[5]There appears to be an error in the equation on page 123 of TSB-88-B. See page 90 of TSB-88-A and (A.2) above or TSB-88-C for the correct expression.

T_t is the total number of grid points measured.

Next we need to know the minimum number of gridded samples required to ensure the service area reliability estimate is accurate. To do so, let's first model each measurement sample as an independent trial with probability of success, *p*, where *p* is the probability that the measurement is above the service threshold. (Remember that the measurement sample is actually a linear average of at least 50 subsamples collected over at least 40 wavelengths.) The number of successes in *n* trials is a binomial random variable that we will designate *X*. If we conduct an experiment with *n* trials and observe *x* successes, the point estimate for *p* is simply *x/n*. However, a point estimate alone tells us nothing about the accuracy of the estimate. What we really need is a measure of confidence that the point estimate, *x/n*, lies in a small interval around *p*. Let's say that we are satisfied with a confidence level of 90% and a confidence interval of +/- .02. Given this confidence level and confidence interval, we want to know the required number of samples. In other words, we require a sufficient number of samples that we can say with 90% confidence that the actual service area reliability lies between +/- 2% of the point estimate.

Using the normal approximation to the binomial distribution, one can show that the required minimum number of samples is approximated by the following [4]:

$$n = \frac{z_{\alpha/2}^2 p(1-p)}{d^2} \tag{A.4}$$

where $z_{\alpha/2}$ is the argument of the unit normal distribution for a confidence of 1-α and *d* is one-half of the confidence interval [4]. For example, for 90% confidence, $z_{\alpha/2} = 1.65$.[6]

Equation (A.4) is not entirely satisfactory because it includes the parameter we want to estimate, *p*. However, the product *p*(1-*p*) will always be less than or equal to 1/4. Thus, the worst case minimum value of *n* is given by

$$= \frac{z_{\alpha/2}^2}{4\,d^2} \tag{A.5}$$

For $z_{\alpha/2} = 1.65$ and d = +/- .02, we find n = 1,702. Thus, we require at least 1,702 samples to achieve the required confidence level and confidence interval. Because most surveys result in some bad data that cannot be used, the survey should be planned for some larger number of gridded measurements, say n = 1750.[7]

[6]The corresponding values for 95% and 99% confidence levels are 1.96 and 2.58, respectively.

[7]The worst case minimum value of *n* occurs when *p* = 0.5, equivalent to 50% coverage and a poor performing system. But the

D. Service Threshold

The receiver threshold for reliable service (e.g., DAQ = 3.4) is usually provided by the manufacturer after the customer sets the threshold for quality of service. For DAQ = 3.4, common thresholds are -101 dBm for analog NPSPAC radios and -106 dBm for digital P25 radios.[8]

E. Test Equipment Characteristics

The test receiver should produce accurate and reproducible measurements. Measurement error should be no greater than 1.5 dB.

To ensure at least 50 subsamples are collected in a relatively short distance (e.g., 100 feet), the receiver must scan quickly or the vehicle must move slowly. As a practical matter, the vehicle must keep up with other traffic, so a fast scanning receiver is mandatory. For example, if the vehicle is moving at 73 feet per second (50 mph) and the desired averaging distance is 100 feet, the receiver must collect one measurement every 37 milliseconds to ensure at least 50 subsamples are collected.[9] When multiple frequencies are measured during the same survey, it may be necessary to extend the collection distance beyond the preferred distance of 100 feet. There is no ironclad rule on the maximum distance for averaging subsample measurements. When multiple frequencies are measured during the same survey, each frequency subsample measurement should be interleaved so the computed average can be applied to the same point in space for each frequency.

Like any radio receiver, the test receiver is susceptible to receiver intermodulation. It is important to eliminate receiver intermodulation in the test receiver so intermodulation signals are not mistaken for over-the-air measurements. Bench testing of typical good quality test receivers reveals that two-tone 3rd-order intermodulation products rise above the system noise floor of -120 dBm when the power of each interfering signal exceeds -40 dBm. To prevent signals above -40 dBm from entering the receiver, one should employ a bandpass or band-reject cavity filter designed to pass the desired signal and reject high-power interfering signals. When it is difficult to separate closely-spaced frequencies via filtering, an attenuator can be used as long as the attenuator does not attenuate the desired signal below the sensitivity of the receiver. Sometimes a combination of filters and attenuators is needed.

All measurements must be corrected during post processing for attenuation created by the filter and external attenuator (if any).

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licensee cannot know the value of *p a priori*, so surveys should always be planned for at least 1750 samples.

[8]The service threshold depends on the receiver's performance in Rayleigh fading, but also on the receiver noise floor which varies between manufacturers and between models.

[9]To this point, we have assumed a narrowband scanning receiver. A wideband sampling receiver is also acceptable provided it has sufficient dynamic range to operate in the presence of strong interferers and it samples fast enough.

F. Route Planning and Gridding

Before planning the survey routes, a theoretical uniform grid should be placed over the service area with grid spacing sufficiently small to ensure at least 1,750 grid tiles (for a 90% confidence interval of +/- 2% for service area reliability). Plan the drive route so that parallel streets are covered with spacing no larger than the grid tile dimension, where possible. Because drive test survey measurements are typically collected continuously along the drive route, there will be more measurements than grid tiles. But to fairly compare service area reliability, we must compare measurements on a uniform grid. For this reason, it is important to grid the randomly distributed measurement data to the uniform grid using a two-dimensional interpolation algorithm.

Grid points that are not accessible during the drive test are simply excluded from the calculation of service area reliability. They count neither as a "pass" or a "fail."

G. Signal Strength Versus Service Quality

Most drive test surveys are designed only to collect signal strength measurements. Unfortunately, an adequate signal strength alone does not guarantee acceptable service. Channel impairments other than weak signals also affect service quality. These include 800 MHz interference, intermodulation interference at the repeater site, delay spread, and simulcast overlap interference. If these and other impairments cannot be eliminated from consideration, it may be necessary to either instrument the drive test receiver system to collect relevant measurements (e.g., bit-error-rate or frame-error-rate) or conduct subjective push-to-talk voice quality tests during the drive test survey.

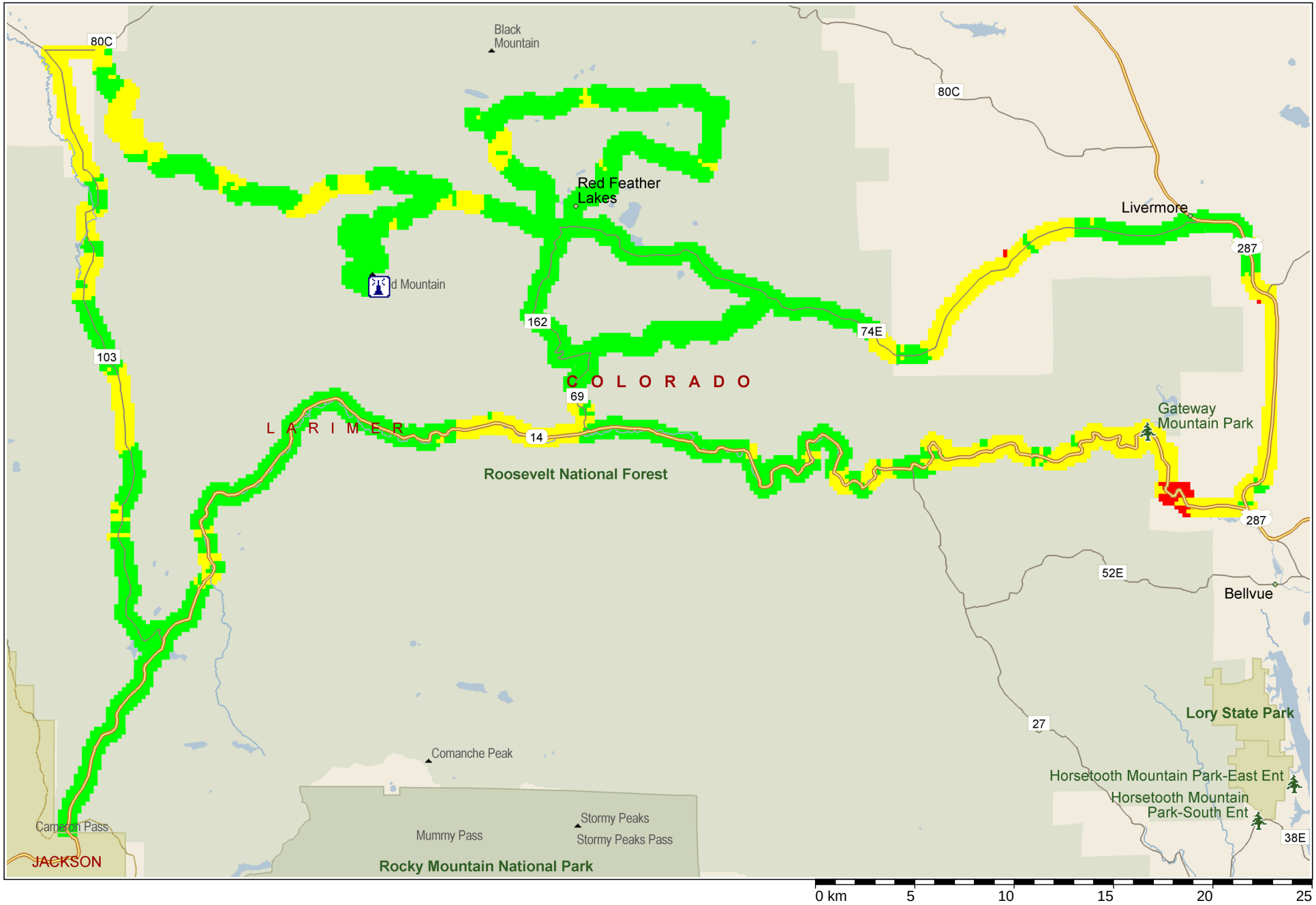
Appendix B - VHF Mobile Outbound Coverage Maps

$C \geq -80$ dBm = Green

-106 dBm $\leq C < -80$ dBm = Yellow

$C < -106$ dBm = Red

VHF Middle Bald Mobile Outbound, -106, -80 dBm = Red, Yellow, Green



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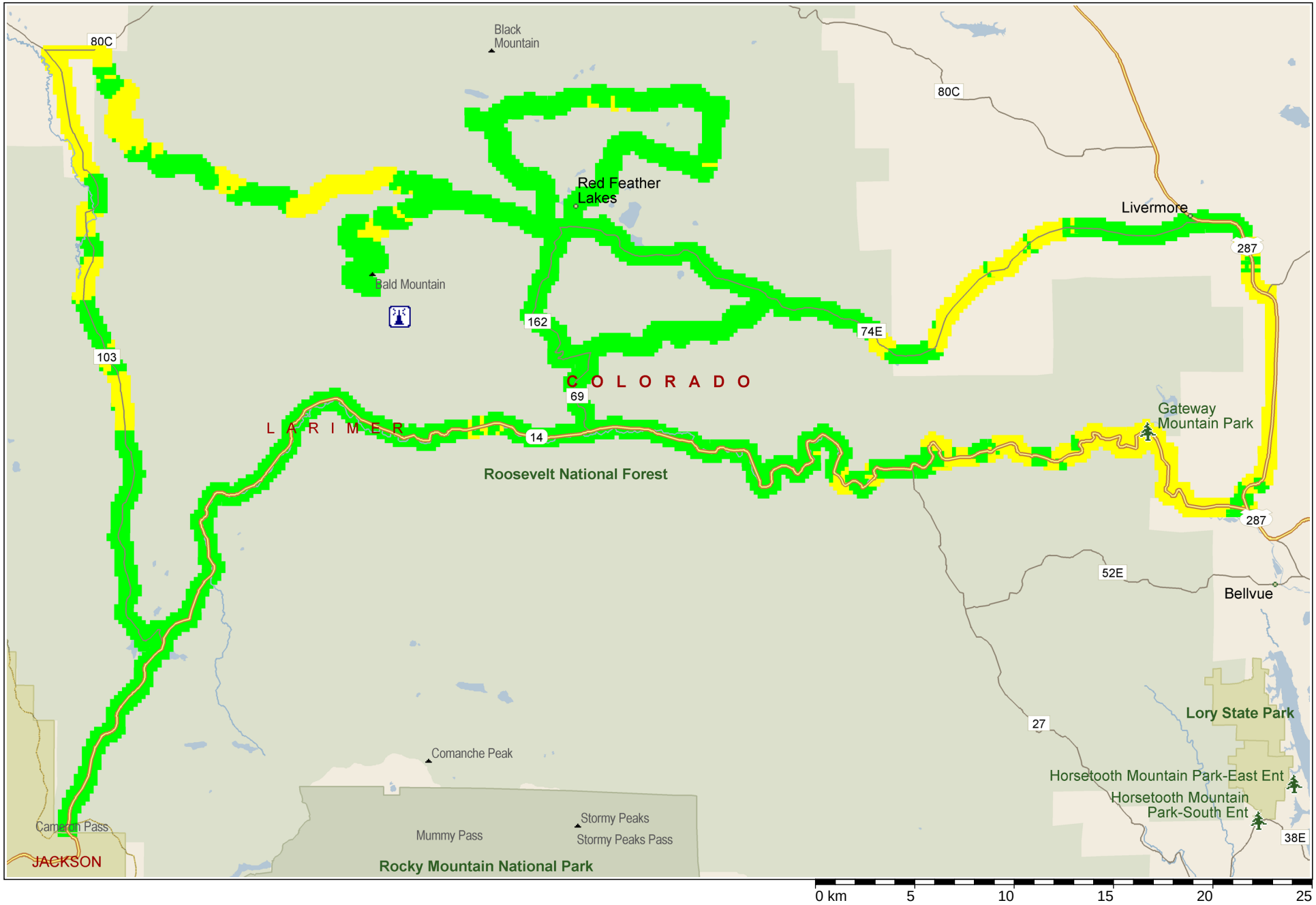
VHF South Bald Mobile Outbound, -106, -80 dBm = Red, Yellow, Green



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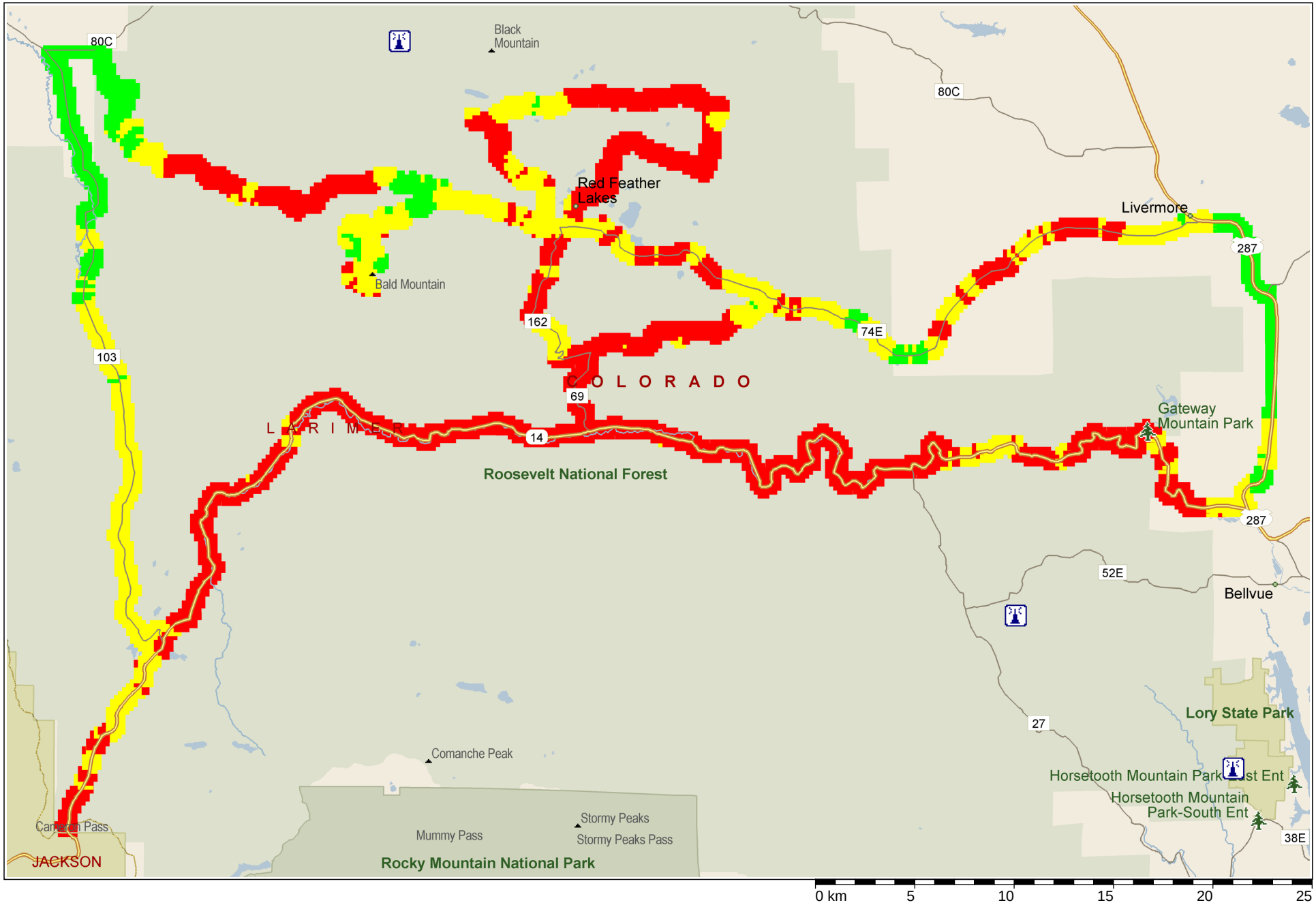
Appendix C - 800 MHz Mobile Outbound Coverage Maps

$C \geq$ -80 dBm = Green

-106 dBm $\leq C <$ -80 dBm = Yellow

$C <$ -106 dBm = Red

800 MHz Existing DTRS Mobile Outbound, -106, -80 dBm = Red, Yellow, Green



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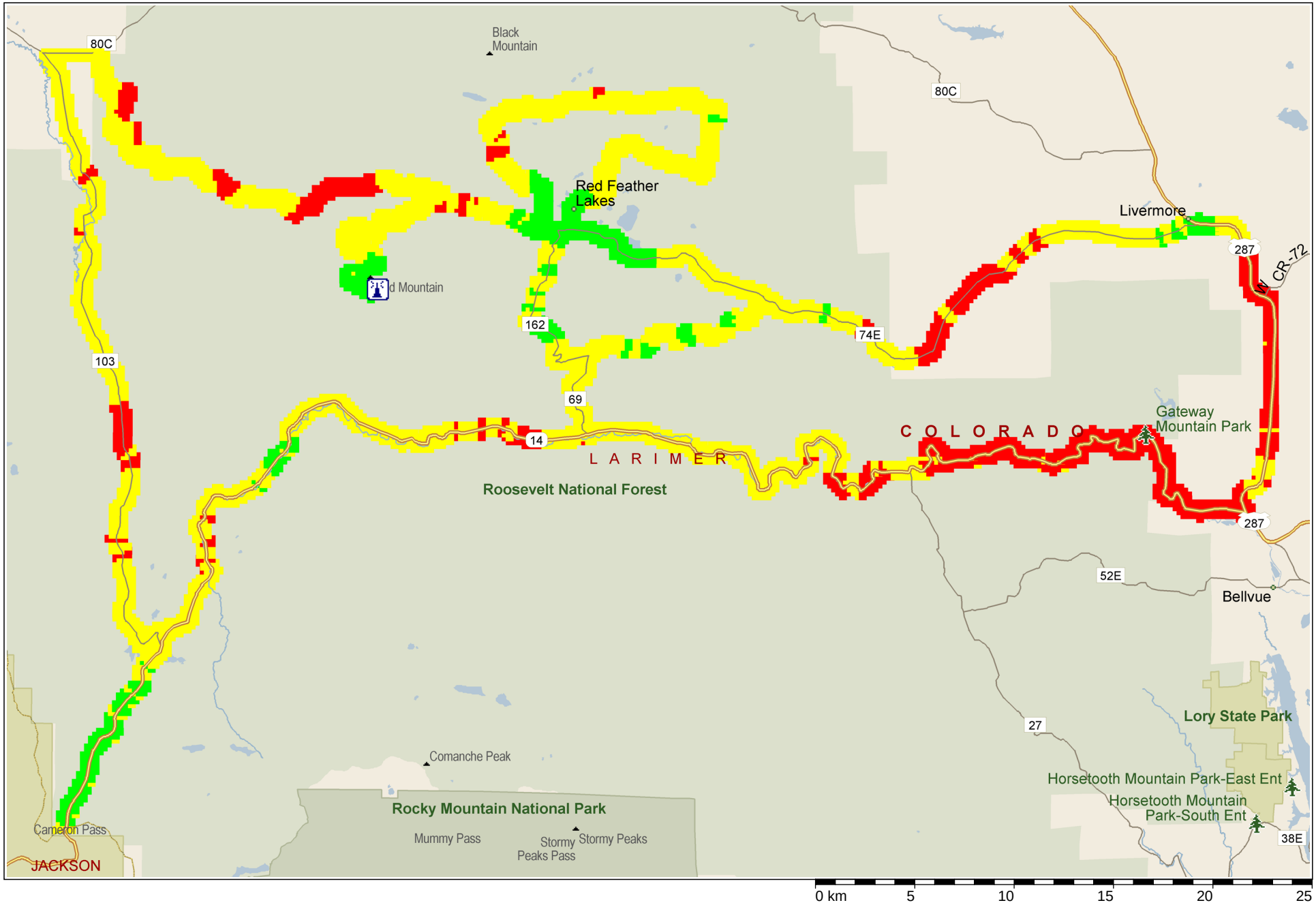
800 MHz Middle Bald Mobile Outbound, -106, -80 dBm = Red, Yellow, Green



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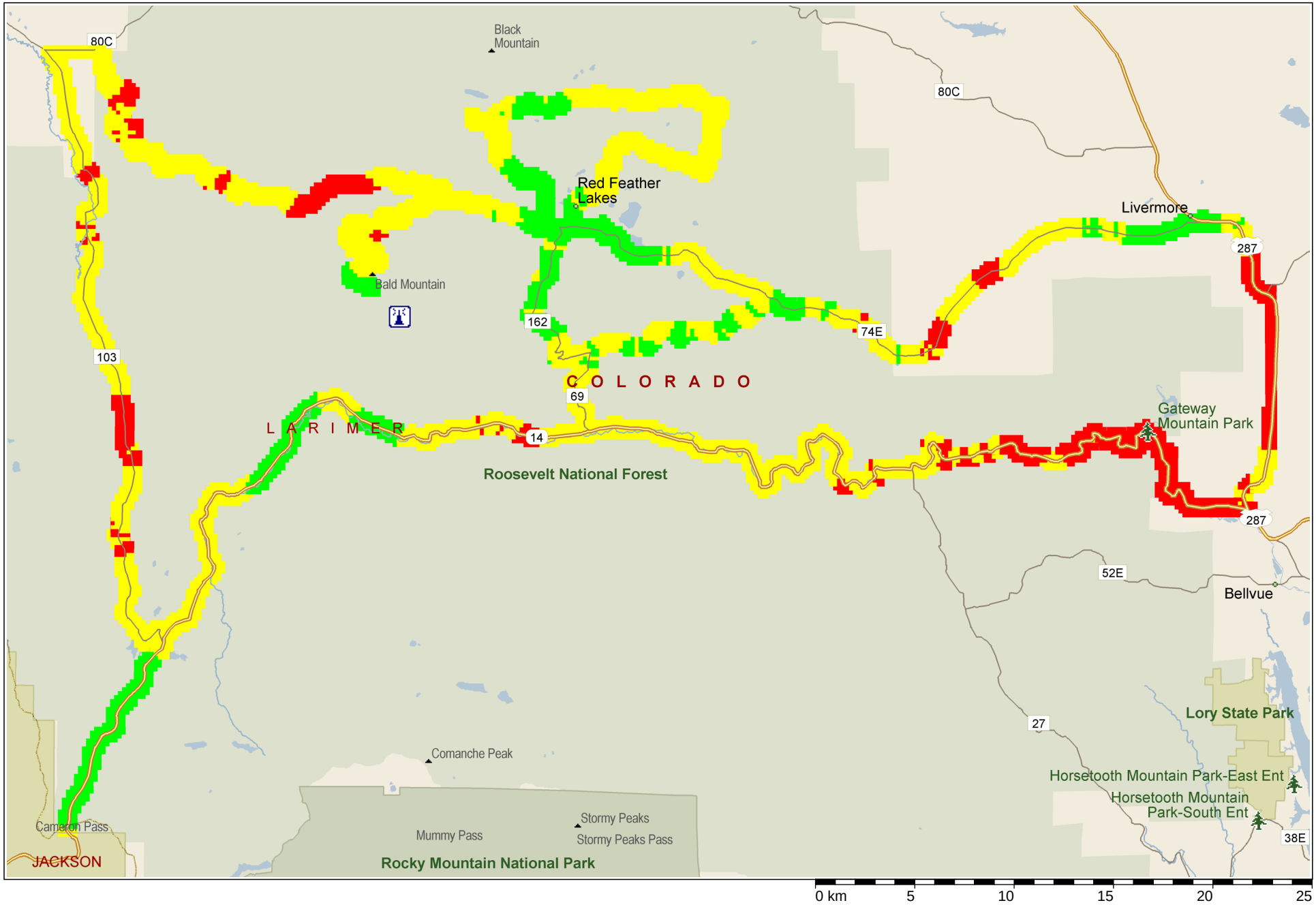
800 MHz South Bald Mobile Outbound, -106, -80 dBm = Red, Yellow, Green



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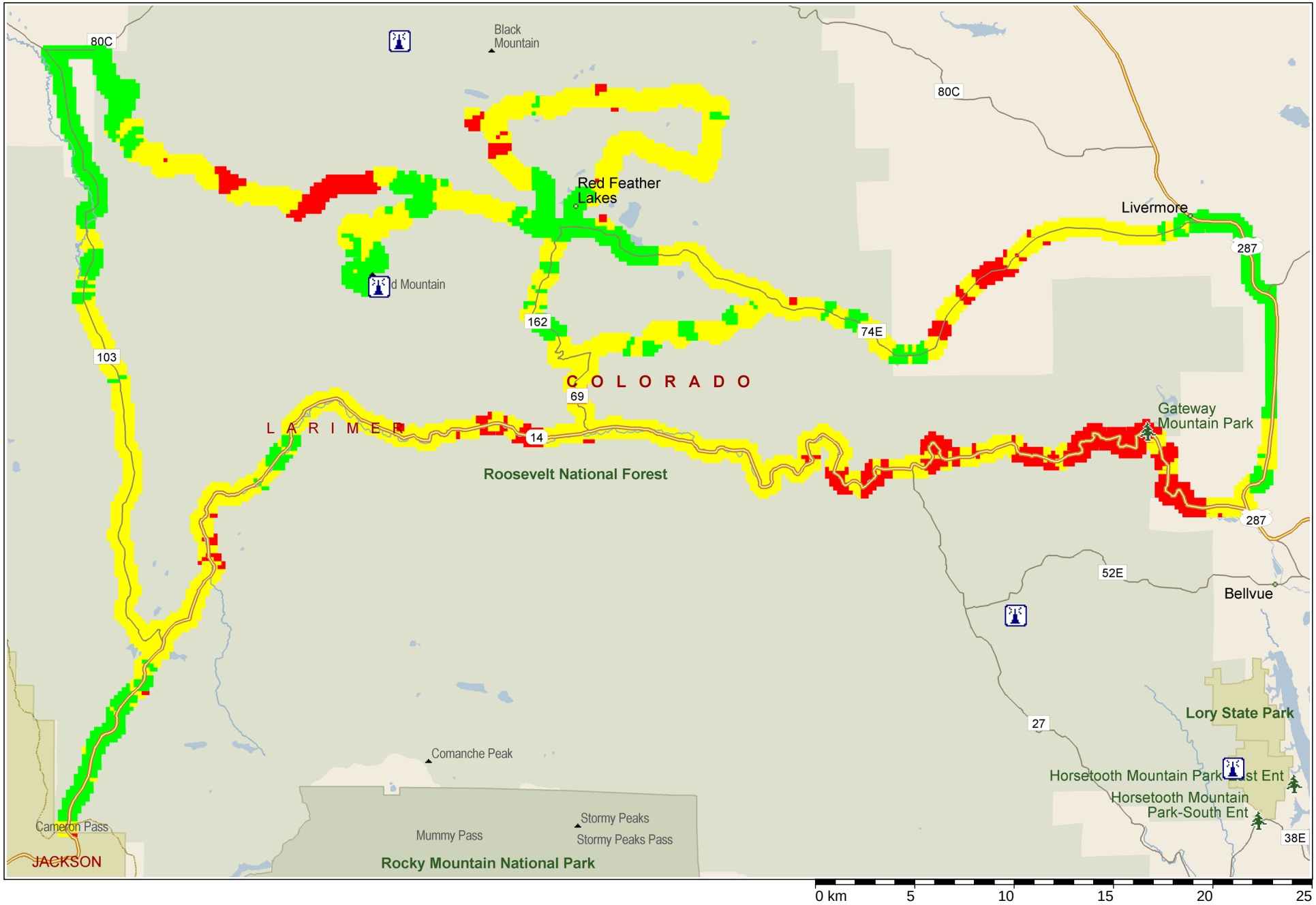
800 MHz Middle Bald Plus DTRS Mobile Outbound, -106, -80 dBm = Red, Yellow, Green



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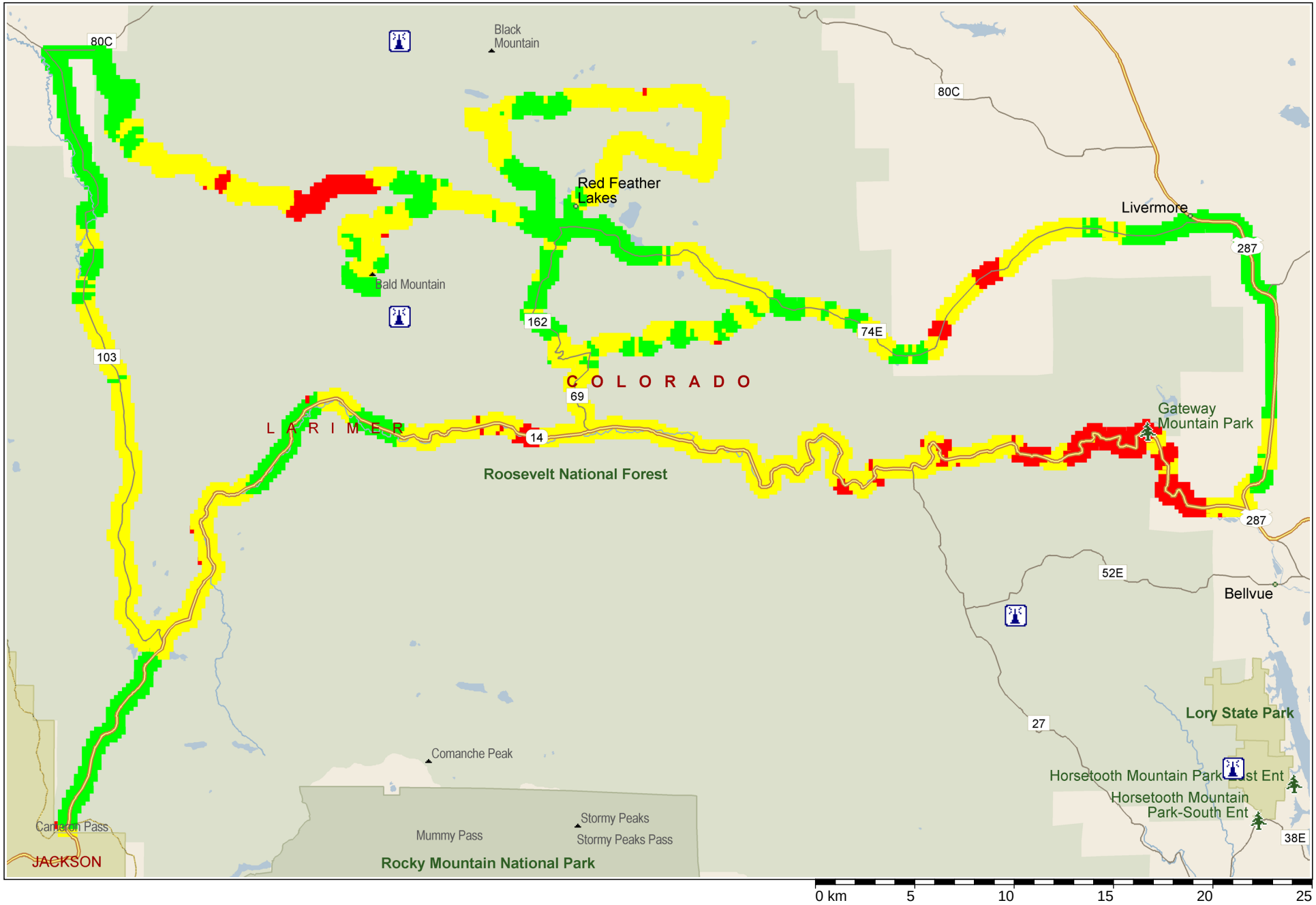
800 MHz South Bald Plus DTRS Mobile Outbound, -106, -80 dBm = Red, Yellow, Green



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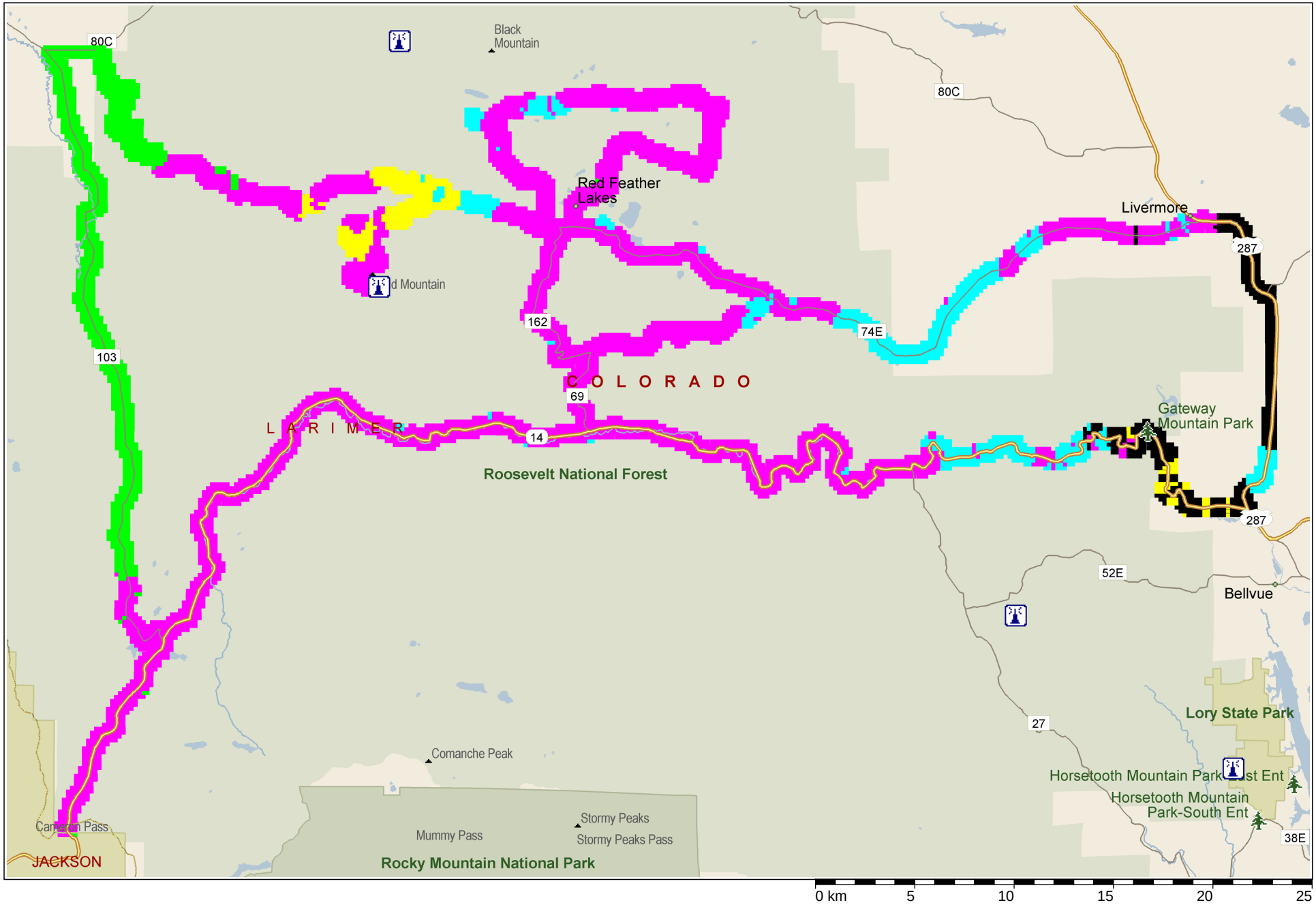
Middle Bald 800 MHz Best Server, MBald=Magenta, Bull=Green, Bear G.=Yellow, Buckhorn=Cyan, Horsetooth=Black



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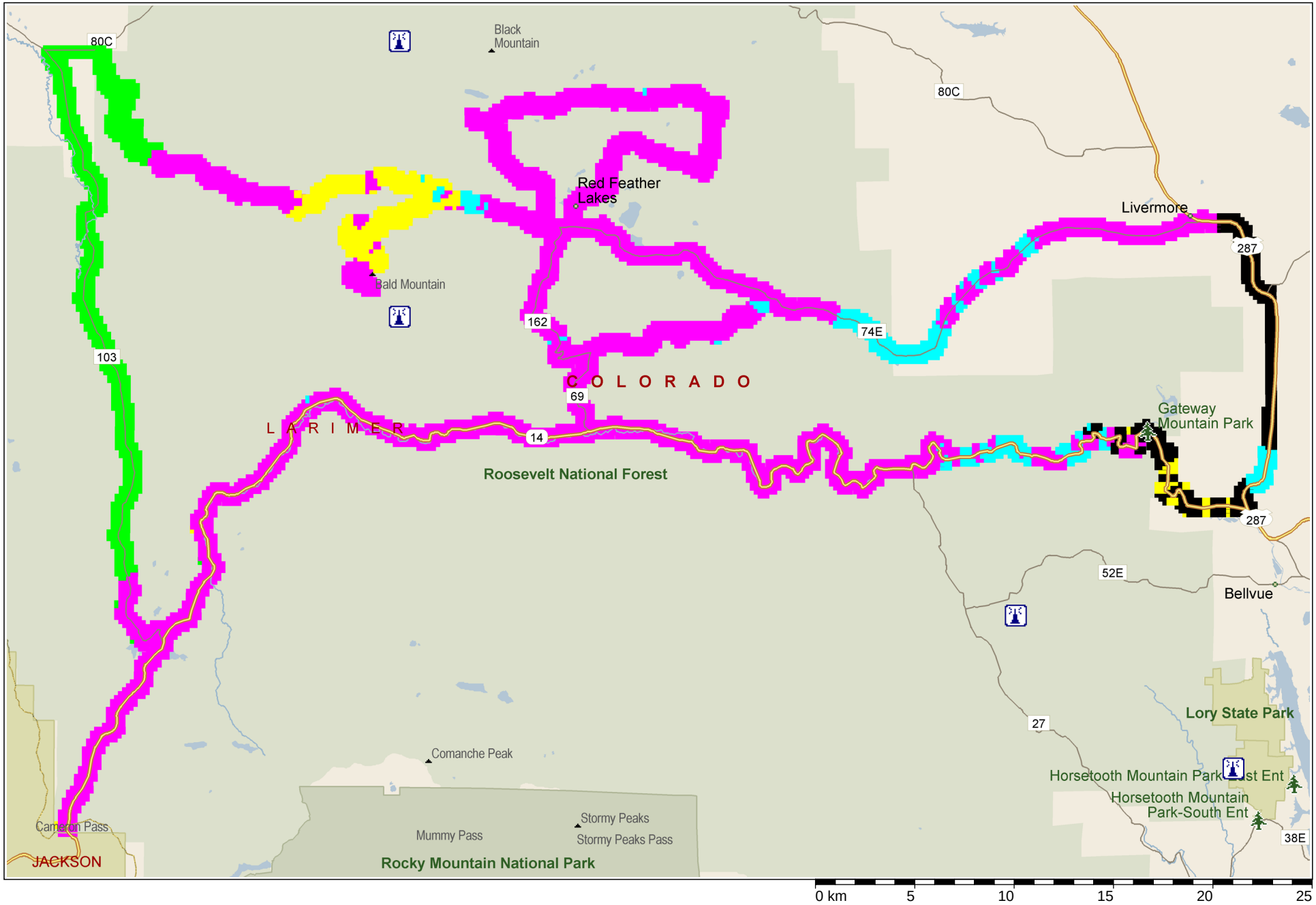
South Bald 800 MHz Best Server, SBald=Magenta, Bull=Green, Bear G.=Yellow, Buckhorn=Cyan, Horsetooth=Black



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