NTIA Report TR-13-496

Broadband Spectrum Survey in the Denver and Boulder, Colorado, Metropolitan Areas

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U.S. DEPARTMENT OF COMMERCE • National Telecommunications and Information Administration

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NOTE ON REISSUE

This was the first in a series of three reports presenting measurement data from three separate spectrum occupancy surveys carried out in 2011 and 2012 as part of ongoing research efforts. In preparing the third report for release, we discovered an incorrect display of the mean system noise and the threshold in some images. The process for generating the images was corrected and the images re-generated. In the reissue of this report, Figures 18, 48, 62, 63, 64, and 66 have been replaced with correctly generated images. The measured data was not affected by the pre-publication processing and remains unchanged; only the display of the mean system noise is changed.

DISCLAIMER

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ABBREVIATIONS/ACRONYMS

ACF	Antenna Correction Factor
ADS-B	Automatic Dependent Surveillance Broadcast
AFSCN	Air Force Satellite Control Network
ANLE	Airport Network and Location Equipment
ARSR	Air-Route Surveillance Radar
ASR	Airport Surveillance Radar
ATC	Air Traffic Control
ATCRBS	Air Traffic Control Radar Beacon System
ATIS	Automated Terminal Information System
ATSC	Advanced Television Systems Committee
AWOS	Automated Weather Observation System
CDF	Cumulative Distribution Function
CCDF	Complementary Cumulative Distribution Function
CW	Continuous Wave
dB	Decibel
dBi	Decibel isotropic
dBm	Decibel milliwatt
dBµV	Decibel micro-volt
DC	Direct Current
DCP	Data Collection Platform
DGPS	Differential Global-Positioning System
DIA	Denver International Airport
DME	Distance Measuring Equipment
DOI	Department of Interior

DSCS	Defense Satellite Communications Systems
DSN	Deep Space Network
DTV	Digital Television
DVA	Department of Veterans Affairs
ELT	Emergency Locating Transmitter
EPIRB	Emergency Position-Indicating Radar Beacons
EPLRS	Enhanced Position Location Reporting System
EVA	Extra-Vehicular Activity
FAA	Federal Aviation Administration
FCC	Federal Communications Commission
FFT	Fast-Fourier Transform
FS-CCDF	Field-Strength, Complementary Cumulative Distribution Function
GHz	Gigahertz
GMF	Government Master File
GOES	Geostationary Operational Environmental Satellites
GPS	Global Positioning System
INMARSAT	International Marine/Maritime Satellite
ISM	Industrial, Scientific, and Medical
ITS	Institute for Telecommunication Sciences
JTIDS	Joint Tactical Information Distribution System
kW	Kilowatt
LMR	Land Mobile Radio
LOS	Line-of-sight
LPTV	Low Power Television
LTE	Long Term Evolution

MDS	Multi-point Distribution Systems
MHz	Megahertz
MLS	Microwave Landing System
MSL	Mean Sea Level
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
NEXRAD	Next-Generation Radar
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
NTIA	National Telecommunication and Information Administration
NTSC	National Television Systems Committee
OSM	Office of Spectrum Management
PCS	Personal Communication System
PDF	Probability Distribution Function
PGM	Precision-Guided Munitions
RBW	Resolution Bandwidth
RF	Radio Frequency
RFID	Radio Frequency Identification
RNSS	Radio Navigation Satellite Service
RSMS	Radio Spectrum Measurement Sciences
SA	Spectrum Analyzer
SAR	Synthetic Aperture Radar
SARSAT	Search and Rescue Satellite Aided Tracking
SGLS	Space-Ground Link System
TACAN	Tactical Air Navigation

TCAS	Traffic Alert and Collision Avoidance System
TDRSS	Tracking and Data Relay Satellite System
TDwFFT	Time-Domain Acquisition with Fast-Fourier Transform Processing
TDWR	Terminal Doppler Weather Radar
TIROS	Television Infrared Operational Satellite
TTC	Telemetry, Tracking and Command
TV	Television
TVWS	Television White Space
U-NII	Unlicensed National Information Infrastructure
UPS	Uninterruptible Power Supply
VBW	Video Bandwidth
VHF	Very-High Frequency
VOR	VHF Omnidirectional Range
WAAS	Wide Area Augmentation System
WAPA	Western Area Power Administration
WGS	Wideband Gapfiller Satellite
WLAN	Wireless Local Area Network
YIG	Yttrium Iron Garnet

BROADBAND SPECTRUM SURVEY IN THE DENVER AND BOULDER, COLORADO, METROPOLITAN AREAS

Chriss Hammerschmidt, Heather E. Ottke[1], J. Randy Hoffman[2]

NTIA is responsible for managing the Federal Government's use of the radio spectrum. In discharging this responsibility, NTIA uses the Radio Spectrum Measurement Sciences system to collect spectrum occupancy data for radio frequency assessments. This report shows measured frequency data spanning spectrum from 108 MHz to 10 GHz in the metropolitan area of Denver, Colorado, during the month of June 2011.

Keywords: land mobile radio (LMR); radar emission spectrum; radio spectrum measurements sciences (RSMS); radio frequency environment; spectrum occupancy; spectrum resource assessment; spectrum survey

1 INTRODUCTION

1.1 Background

The National Telecommunications and Information Administration (NTIA) is responsible for managing the Federal Government's use of the radio spectrum. Part of this responsibility is to establish policies concerning spectrum assignment, allocation, and use; and to provide the various departments and agencies with the guidance to ensure that their conduct of telecommunications activities is consistent with these policies [1]. In discharging this responsibility, NTIA 1) assesses spectrum utilization, 2) identifies existing and/or potential compatibility problems among the telecommunication systems that belong to various departments and agencies, 3) provides recommendations for resolving any compatibility conflicts that may exist in the use of the frequency spectrum, and 4) recommends changes to promote spectrum efficiency and improve spectrum management procedures.

Since 1973, NTIA has been collecting data on radio frequency spectrum utilization. The Radio Spectrum Measurement Sciences (RSMS) system was developed by NTIA to perform thorough and accurate spectrum occupancy measurements in virtually any location in a broad range of spectrum bands. These measurements support agency needs such as Federal spectrum management, usage assessments, interference resolution, and propagation research support. The RSMS-4 measurement vehicle used to conduct the measurements reported here is the fourth generation mobile measurement laboratory developed by NTIA and is equipped with state-of-the-art instrumentation, measurement methods, and analysis capabilities.

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1.2 Purpose of this Survey

Under U.S. Department of Commerce Departmental Organizational Order 25-7 [2], one of the assigned functions of the Institute for Telecommunication Sciences (ITS) is to acquire, analyze, synthesize, and disseminate data and perform research in general on the description and prediction of electromagnetic transmission, noise, and interference, and on methods for improving the use of the spectrum for telecommunication purposes.

RSMS measurement activities are carried out as part of ongoing research projects undertaken to fulfill the statutory directive that NTIA conduct research and analysis in the general field of telecommunications sciences. They may also be carried out at the direction of the Office of Spectrum Management (OSM), either on behalf of another Federal agency that has requested assistance from OSM or in support of OSM's mission to meet the spectrum management requirements of NTIA.

This survey of spectrum occupancy in the Denver and Boulder, Colorado, metropolitan areas was conducted in 2011 as part of ongoing research efforts. The spectrum occupancy data presented in this report does not include identification of specific emitters. The data are provided for the spectrum management community to enable a better understanding of how telecommunication systems use the licensed and unlicensed spectrum, and to make available information on current frequency band usage.

These measurements were not intended to assess the feasibility of using alternative services or systems in a band. To generalize spectrum occupancy measurements for such analysis, further consideration must be given to the spectrum management procedures and types of missions performed in each band.

1.3 Report Layout

Section 2 begins by describing criteria used to select a spectrum survey measurement site and describes the measurement site selected for the Denver, CO Metropolitan Area, spectrum survey. The section also gives a brief description of the measurement system along with the measurement parameters for this spectrum survey. Section 3 presents the measurement results followed by a discussion of frequency bands, the types of signals that exist in the bands and notes about the measurement graphs. Appendix A explains the calculations for the graphs shown in Section 3. A description of the RSMS-4 system is given in Appendix B. Appendix C shows results for mobile measurements performed in the greater metropolitan Denver, CO, area and a mobile measurement in the immediate vicinity of this spectrum survey. Finally, a comparison between the static measurements of this survey and mobile measurements is given to enable the reader to better understand static occupancy measurements taken at one location versus mobile occupancy measurements taken across a specific area.

2 MEASUREMENTS IN THE DENVER METROPOLITAN AREA

2.1 General Site Selection

The area chosen for a spectrum survey will affect measured spectrum occupancy. For example, measurements taken in one metropolitan area, such as Denver, CO, [3] or Los Angeles, CA, [4] may not represent activity in other metropolitan areas. Some metropolitan areas will lack strong emissions from maritime radionavigation sources or extensive military operations. On the other hand, cities such as San Diego [5] or San Francisco [6], with major naval installations, will show higher levels of usage in bands supporting those operations. Emissions from the following sources are commonly observed during a spectrum survey:

- Land-mobile, marine-mobile, and air-mobile communications radios
- Terrestrial, marine, and airborne radars, and airborne radio transmitters
- Radionavigation emitters, such as Tactical Air Navigation (TACAN) and VHF Omnidirectional Range (VOR), either from ground or airborne transmitters within the range of our measurement system.
- Cellular, broadband wireless, and trunked communication systems
- Broadcasting transmitters such as digital television (DTV) and multi-point distribution systems (MDS, wireless cable television (TV))
- Industrial, scientific, and medical (ISM) sources, including vehicular tracking systems, welders, and microwave ovens
- Unlicensed National Information Infrastructure (U-NII) systems
- Common carrier (point-to-point) microwave signals
- Satellite earth station uplink transmissions

Potential emissions not normally receivable during spectrum surveys may include:

- Satellite downlink emissions
- Galactic and solar noise
- Some types of spread spectrum signals (such as Global Positioning System codes (GPS))
- Licensed radio transmitters that are turned off
- Receive-only systems, passive sensing systems and systems used for radio astronomy observations.

Choice of measurement site within an area will also affect measured spectrum occupancy. In an area with heavy foliage, rough terrain, or widely dispersed transmitters, multiple measurement locations may be required to accurately characterize usage.

The measurement site must be carefully chosen to intercept a large majority of the signals in the area and to minimize logistical problems. To intercept a large majority of signals in the area the site should:

1. Provide line-of-sight (LOS) coverage so that the probability of intercepting weak signals, such as mobile units, is maximized

2. Limit the number of nearby transmitters to minimize intermodulation or saturation problems, even if preselection and/or filtering is used

3. Limit sources of man-made noise such as impulsive noise from automobile ignition systems and electrical machinery

Primary logistical considerations are:

1. Commercial power to decrease the probability of power interruptions and increase the probability of interruption-free measurements

2. Security for personnel, vehicle, and electronic hardware

The ideal site is a well-illuminated, fenced, and patrolled area that satisfies all primary site-selection considerations listed above and has reasonable access to lodging for the operating personnel.

Spectrum occupancy fluctuates over time for individual assignments and across bands. For example, frequencies assigned to law enforcement may be used intermittently but are needed for special events. During a special event, such as an emergency, disaster, Olympic Games [7], or Presidential activities, spectrum requirements may change around that event. Regardless of usage, such dedicated channels must be available for any safety-of-life functions and are a spectrum requirement.

Spectrum measurements provide data on expected signal levels and probability of occurrences. Such information is difficult to obtain from the Federal Communications Commission (FCC) or Government Master File (GMF) frequency assignment databases, or from an understanding of spectrum management procedures.

2.2 Denver Metropolitan Area Measurement Site Description

The selected measurement site reported here is in Arvada, CO. The name of the location is Hackberry Hill and it is located about 12 km from the center of the Denver metropolitan area. The site is owned by the Exempla Colorado Lutheran Home Health Care Center. Their building is situated to the west of the measurement location and is one story high. During the tests, the antenna masts were raised approximately 10 m (30 ft.) to get an unobstructed view of the surrounding area.

Arvada is a suburb of the Denver metropolitan area. It is located between the foothills of the Rocky Mountains and the Great Plains. The measurement location is shown in Figure 1 and the latitude and longitude are 39°49′34.53″ N and 105°04′55.74″ W. The elevation at this location is 1600 meters (5249 feet) above mean sea level (MSL). There were no nearby fixed transmitters. The closest DTV transmitter is approximately 16.9 kilometers (10.5 miles) from the measurement location.

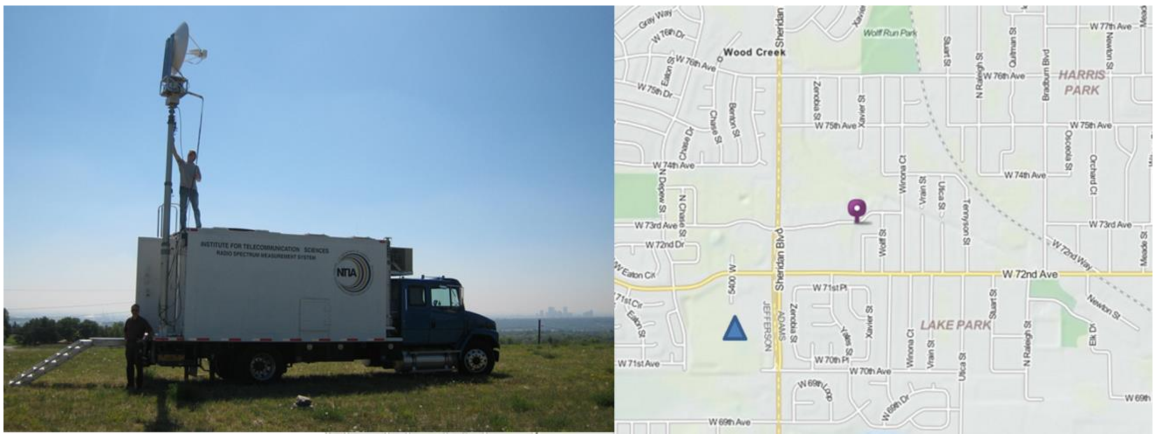

Figure 1. MapQuest® map and picture showing the Arvada measurement location (blue triangle).

2.3 Measurement System Description

The spectrum survey was conducted from June 7, 2011 to June 29, 2011. This ensured that recently developed measurement software and all equipment were functioning optimally and that any suspect data could be retaken. The measurement software includes a scheduler so that some bands could be measured more often than others. For example, LMR activity occurs throughout the day but is intermittent and therefore should be measured as often as possible. Television bands can show diurnal variations but are on almost all the time and so are scheduled to be measured at different times during the day and at night but may be measured less frequently than LMR bands. Some radar bands are not very active in the Denver metropolitan area and so are not measured often. The measurement schedule was adjusted to obtain a maximal amount of measurements in heavily used bands.

Each band is measured with a hardware configuration and measurement algorithms specifically designed to give the most useful information about the particular type(s) of signal expected in a frequency sub-band. The measurement hardware and system parameters considered for each signal type and frequency band include: antennas, sweep time, measurement bandwidth, detector mode, measurement repetitions, preselector filters, and preamplifier paths. Some bands contain multiple signal types, which require tailored measurement algorithms to address the specific characteristics of the different types of radio emitters and, therefore, some bands may appear more than once in the report.

The RSMS-4 measurement software is automated to control instrument operation and data capture for each frequency sub-band. The measurements are repeated according to signal intercept probability, signal variability, significance of signal-type and how often it changes, the need for data in specific bands, and efficiency of system resources.

Two separate systems are used. The schematics for both systems are shown in Figure 2. The first system, the LMR system, measures only LMR narrowband signals below 500 Megahertz (MHz) using the following fixed filters: 108–116 MHz, 138–174 MHz, 216–225 MHz, and 406–420 MHz. A discone antenna with a frequency specification from 25 MHz to 1300 MHz is used with the LMR system. These bands are measured consecutively and as often as possible.

The second system, named the broad-frequency system, measures wideband television and LMR signals below 500 MHz and all other signal types from 500 MHz to 10,000 MHz. The broad-frequency system is a more complex system. The preselectors incorporate digitally-tuned, yttrium iron garnet (YIG) and fixed filters in the system. There are different amplifiers for each selected hardware path. A discone antenna similar to that used in the LMR system is used with the broad-frequency system for measurements below 1000 MHz and an omni-directional antenna with a frequency specification from 300 MHz to 18,000 MHz is switched into the broad-frequency system for measurements above 1000 MHz. Measurements of fixed point-to-point microwave transmitters in their allocated frequency bands use a one meter dish antenna with approximately 30 decibels relative to isotropic (dBi) of gain. The broad-frequency system is used for these measurements.

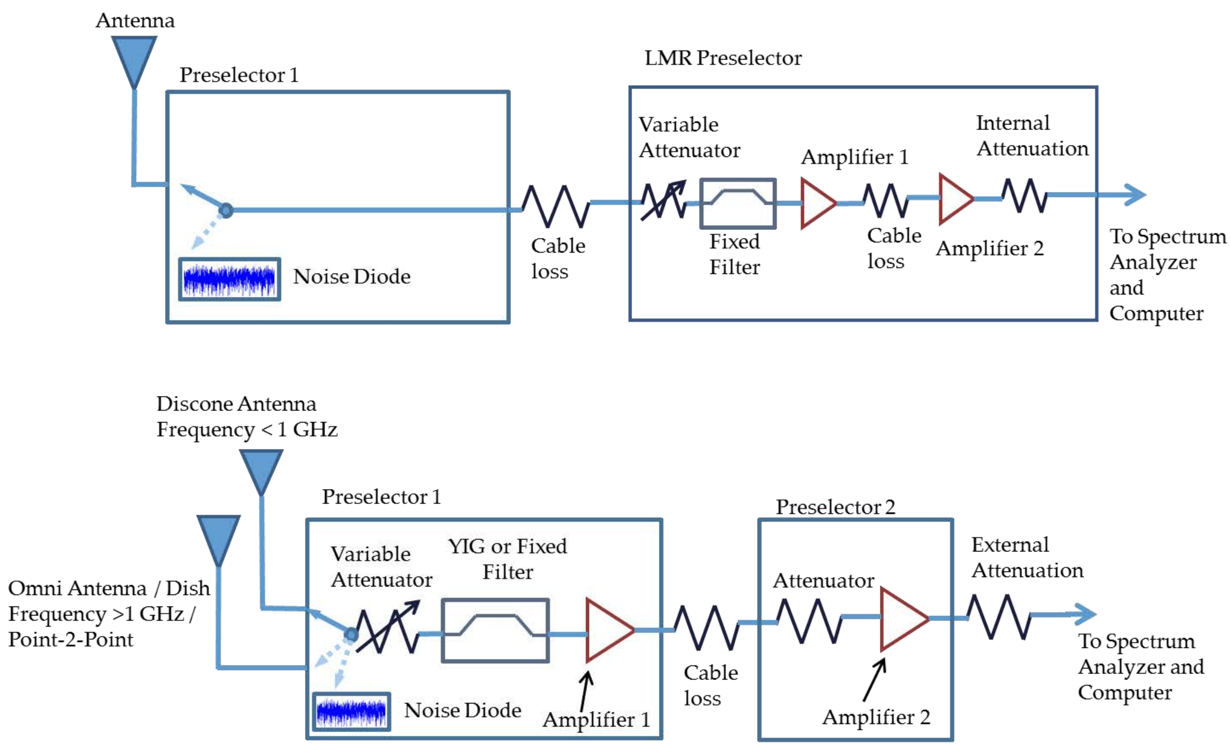

Figure 2. System schematic for the LMR system and the broad-frequency system.

The preselector/preamplifier unit, schematically depicted in Figure 2, serves the purposes of extending the dynamic range, improving measurement system sensitivity, and reducing measurement system responses to signals outside the measurement band. The variable attenuator in the first preselector is used to adjust the upper and lower bounds of the dynamic range of the measurement system. More attenuation is used in bands where strong signals may overload the measurement system, and less attenuation is used in bands with weaker signals. RF bandpass filters also help prevent system overloads by limiting the power from out-of-band emissions. The first amplifier is designed to overcome the cable loss and the amplifier in the second preselector is designed to overdrive the spectrum analyzer (SA) noise figure. The SA acquires signals and transfers information to a computer. The computer software controls instrument configurations, executes measurement routines, records the measured data, and provides real-time system logs of the measurement start and stop times and any measurement problems that may occur.

Four tailored algorithms are used for these measurements: 1) a time-domain acquisition with fast Fourier transform (FFT) processing algorithm (TDwFFT), 2) swept-spectrum measurement algorithm, 3) stepped-spectrum measurement algorithm, and 4) an azimuthal-scanning measurement algorithm. Measurements of frequencies below 500 MHz, independent of the system, use the time-domain acquisition with FFT processing to minimize the effects of impulsive noise. The swept-spectrum measurement algorithm is a general purpose algorithm and is used in bands with multiple signal types or where swept measurements are valid for the emission type. The stepped-spectrum measurement algorithm is used in bands where radar signals exist, and the azimuthal-scanning measurement algorithm was developed to measure fixed point-to-point microwave emissions.

The LMR system measured two scheduled events: a calibration of the system and actual measurements. Events will be described below. Measurements were repeated on an ongoing basis for the full month. These bands were measured approximately 1500 times. Calibrations were performed a minimum of every 12 hours for both the LMR system and the broad-frequency system to ensure the systems were operating correctly. Calibrations were accomplished using internal noise diodes and a Y-factor technique [3].

The broad-frequency system was set up to measure the 42 scheduled events shown in Table 1 Column 1 shows the event number. Column 2 is a brief description of the type of measurement and the measurement algorithm used; for example, event 1 was a calibration in the frequency bands from 116–138 MHz, 406–420 MHz, and 420–476 MHz and was measured using the TDwFFT algorithm. Event 14 was a measurement in the frequency band from 763 to 1000 MHz (which contains signals such as cellular uplinks and downlinks, ISM bands and other miscellaneous signals) and was measured using the swept-spectrum measurement algorithm. These events are called by a scheduler, which schedules each event using the timing parameters shown in columns 3 and 4 of Table 1. Column 3 shows how often the scheduler repeated a measurement. Column 4 shows the minimum number of hours between measurements and Column 5 shows the total number of times the measurement was made during the course of the survey.

For example, measurements of TV bands were repeated ten times during the survey to capture possible variations in the signal and to capture emissions during the day and at night. Radar bands were measured every 54 hours since radars in this area typically do not move to different locations and some radar bands are not occupied in this geographical area. This interval also ensured that we measured some radars in the evening to observe variations. Measurement events under 500 MHz were repeated as often as possible. The following frequency bands, designated by the 0 in column 4, were also measured as often as possible:

- Cellular_Misc[3]_763–1000 MHz cellular bands
- Narrowband_1000–2000 MHz
- Narrowband_2000–2700 MHz
- Narrowband_2900–4200 MHz
- Misc_4400–5000 MHz
- Misc_5000–7000 MHz
- Misc_7000–8000 MHz
- Misc_8000–9000 MHz
- Misc_9000-10000 MHz

Table 1. Scheduled events for the broad-frequency system.

Event	Description	How measurement is repeated	Minimum Hours Between	Total Times Measured
1	Calibration_116–138_225–406_420–476MHz (TDwFFT)	Repeat Ongoing	12	14
2	Measurement_116–138_225–406_420–476MHz (TDwFFT)	Repeat Ongoing	0	41
3	Calibration_TV_174–216_476–500MHz (TDwFFT)	Repeat 10x	12	10
4	Measurement_TV_174–216_476–500MHz (TDwFFT)	Repeat 10x	12	10
5	Calibration_TV_500–608_614–763MHz (Swept)	Repeat 10x	12	10
6	Measurement _TV_500–608_614–763MHz (Swept)	Repeat 10x	12	10
7	Calibration_TVWS_180–210MHz (TDwFFT)	Repeat 10x	12	10
8	Measurement _TVWS_180–210MHz (TDwFFT)	Repeat 10x	12	10
9	Calibration_TVWS_500–608_614–763MHz (Swept)	Repeat 10x	12	10
10	Measurement_TVWS_500–608_614–763MHz (Swept)	Repeat 10x	12	10
11	Calibration_Radar_420–450MHz (Stepped)	Repeat Ongoing	54	7
12	Measurement_Radar_420–450MHz (Stepped)	Repeat Ongoing	54	7
13	Calibration_Cellular_Misc_763–1000MHz (Swept)	Repeat Ongoing	12	14
14	Measurement_Cellular_Misc_763–1000MHz (Swept)	Repeat Ongoing	0	38
15	Calibration_Radar_854–928MHzMHz (Stepped)	Repeat Ongoing	54	7
16	Measurement_Radar_854–928MHzMHz (Stepped)	Repeat Ongoing	54	7
17	Calibration_Narrowband_1000–2000MHz (Swept)	Repeat Ongoing	12	14
18	Measurement_Narrowband_1000–2000MHz (Swept)	Repeat Ongoing	0	40
19	Calibration_Radar_1215–1390MHz (Stepped)	Repeat Ongoing	54	7

[3] Misc refers to other miscellaneous signals that may be present in this frequency band.

20	Measurement_Radar_1215–1390MHz (Stepped)	Repeat Ongoing	54	7
21	Calibration_Narrow_2000–2700MHz (Swept)	Repeat Ongoing	12	7
22	Measurement_Narrow_2000–2700MHz (Swept)	Repeat Ongoing	0	14
23	Calibration_Radar_2700–2900MHz (Stepped)	Repeat Ongoing	54	40
24	Measurement_Radar_2700–2900MHz (Stepped)	Repeat Ongoing	54	7
25	Calibration_Radar_2900–3650MHz (Stepped)	Repeat Ongoing	54	7
26	Measurement_Radar_2900–3650MHz (Stepped)	Repeat Ongoing	54	7
27	Calibration_Narrowband_2900–4200MHz (Swept)	Repeat Ongoing	12	7
28	Measurement_Narrowband_2900–4200MHz (Swept)	Repeat Ongoing	0	14
29	Calibration_Radar_5250–5925MHz (Stepped)	Repeat Ongoing	54	40
30	Measurement_Radar_5250–5925MHz (Stepped)	Repeat Ongoing	54	7
31	Calibration_Misc_4400–5000MHz (Swept)	Repeat Ongoing	12	7
32	Measurement_Misc_4400–5000MHz (Swept)	Repeat Ongoing	0	38
33	Calibration_Misc_5000–7000MHz (Swept)	Repeat Ongoing	12	14
34	Measurement_Misc_5000–7000MHz (Swept)	Repeat Ongoing	0	38
35	Calibration_Misc_7000–8000MHz (Swept)	Repeat Ongoing	12	14
36	Measurement_Misc_7000–8000MHz (Swept)	Repeat Ongoing	0	38
37	Calibration_Misc_8000–9000MHz (Swept)	Repeat Ongoing	12	14
38	Measurement_Misc_8000–9000MHz (Swept)	Repeat Ongoing	0	38
39	Calibration_Misc_9000–10000MHz (Swept)	Repeat Ongoing	12	14
40	Measurement_Misc_9000–10000MHz (Swept)	Repeat Ongoing	0	38
41	Calibration_Radar_8500–10000MHz (Stepped)	Repeat Ongoing	54	7
42	Measurement_Radar_8500–10000MHz (Stepped)	Repeat Ongoing	54	7

Each scheduled event is described by a unique set of parameters that include the instrument setup, measurement events, and data collection subroutines. Each event also contains measurement parameters such as start and stop frequency, sweep time, the number of points per trace, the resolution bandwidth (RBW), the video bandwidth (VBW), detector type, filter type, and preselector attenuation. Table 2 shows generic parameters for scheduled events for the different measurement algorithms discussed above.

The swept, stepped, and azimuthal-scanning algorithms have similar parameters because they use the spectrum mode of the spectrum analyzer. The time-domain parameters are different because they use the basic mode of the spectrum analyzer.

Table 2. Generic event parameters for measurement algorithms.

Parameter	Swept-spectrum	Stepped-spectrum	Azimuthal-scanning
RBW (MHz)	0.3	1.0	1.0
VBW (MHz)	0.3	1.0	1.0
Start Frequency (MHz)	4400	2900	4000
Stop Frequency (MHz)	5000	3650	5000
Sweep Time (ms)	1000	12000	1000
Points/Trace	2001	8192	1001
Preselector Antenna Ports	2-1	2-1	2-1
Detector Type	Average	Positive Peak	Average
Filter Type	Fixed	Fixed or Tunable	Fixed or Tunable
Preselector Attenuation (dB)	0	Auto	None
Sweeps/Event	100	751	
Step size (MHz)		1	
Scan Mode			Stepped
Angular Resolution (degrees)			1
Azimuth Start (degrees)			180
Azimuth Stop (degrees)			-180
Median Threshold (dB)			2
Elevation (degrees)			0

Time-domain parameter	FFT processing
RBW (kHz)	6.25
Span (kHz)	4.1
1st Channel (MHz)	108
kHz/Channel (kHz)	6.25
Channels/Band	640
Points/RBW	10
Traces/Median	5
Event Acquisition Time (min)	1.1
Time/median (sec)	0.9
Window type	Flattop
Preselector Attenuation (dB)	30
Preselector Antenna Ports	2-1
Filter Center Frequency (MHz)	110

After the survey data has been taken, additional processing is necessary to obtain statistical descriptions of the data. These processing steps are briefly described in the following section.

3 MEASURED DATA

There are over 220 individual processed events. Where possible, we have combined events to minimize the report graphs while providing useful clarity. The graphs are generated from the measurement data using a MATLAB® script developed at ITS. This script has limitations, such as layout restrictions that may result in label truncation or displacement. The script also has advantages, such as being able to pull information from the FCC and GMF databases to show assignments directly in the report graph.

The frequency allocations, shown in the yellow strips at the top of each figure, are taken from the United States Frequency Allocation Chart [8] in which the names of primary services are printed in capital letters and secondary services are printed in upper and lower case. The numbers shown above the allocation bar are the band-edge frequencies for the allocations. Some of the frequency allocation information is truncated in the boxes above the graphs due to the band edge labels.

There are three presentations of data in this report. Swept-spectrum and TDwFFT data are shown using three graphs; stepped-spectrum measurements are shown using two graphs; and azimuthal-scanning plots are shown on one plot.

When three graphs are shown on a page, the top graph is the statistical description of the data at each frequency: the maximum value (blue trace), the mean value (black trace), the median value (green trace), the minimum value (red trace), and the mean system noise (magenta trace). These are referred to in this report as the M4 statistics plots. These were introduced in [3], [4], [5], and [6] as Swept/m3 or Swept/m4 measurements. The middle graph shows field strength as a function of frequency and time and is commonly referred to as a waterfall plot. These are displayed as contour plots having 20 contoured field-strength levels. Red values indicate relative maximum field strength levels, and blue values indicate relative minimum field strength levels. The bottom graph shows the complementary cumulative distribution functions of the electric field strength (FS-CCDFs) as a function of frequency. The probability that a measured signal exceeds the specified field-strength is shown in the legend.

The threshold level, shown by the dashed black trace in the bottom plot, is used to display the data in the middle plot (field strength as a function of time and frequency). Threshold levels are either set to minimize the display of impulsive noise without excluding low-level signals, such as in frequencies below 500 MHz or set to a field-strength level that is likely to be exceeded by the system noise less than 0.01% of the time. The thresholds set for various bands are summarized in Table 3 and are restated above the FS-CCDF plots. Typically FS-CCDFs can be used to understand signal types and are useful for displaying the probability that a signal exceeds a certain field-strength level. The spacing of the lines gives us an indication as to whether a signal is Gaussian-distributed, pulsed continuous-wave (CW), or another signal type and also is indicative of the measurement algorithm used.

Table 3. Threshold levels for measured frequency ranges.

Frequency Range (MHz)	Threshold Level (dB)
108 – 174	10
174 – 216	8
216 – 261	10
261 – 500	8
500 – 4200	6
4400 – 7000	1
7000 – 10000	1.5

Radar or stepped measurements are shown using two graphs. The top graph shows the M4 statistics and peak system noise statistics, and the bottom graph shows the individual traces so that changes in the radar characteristics, such as frequency tuning, can be differentiated.

Fixed point-to-point microwave measurements taken with the azimuthal-scanning algorithm show only one plot in which the frequency is plotted on the x-axis and the azimuthal angle is plotted on the y-axis. Relative power is displayed by contour levels. This graph is used to show the angular dependence of these transmissions.

Data presented in these graphs is affected by both the measurement parameters given in Table 2 and the post-processing algorithms. Each graph is plotted with a unique field strength scale to show more detail in the plots. Field strength is referenced to the antenna input and calculated so that measurements from different systems can be compared. The notation "Referenced to antenna input – adjusted for attenuation" in each graph means that any losses due to the antenna or cables and attenuators between the preselector and the input of the antenna are accounted for. The azimuthal-scanning measurements were taken in the vertical polarization only due to time constraints. These plots may show signals received by the antenna side-lobes, readily identified as data seen across all azimuthal angles at one frequency.

The data presentation in each graph is intended to best describe the signal environment within its measured frequency band or bands. The measurement range of the receiving system is dependent on the system sensitivity in each band. Based on the measurement parameters, algorithms, and statistical analysis, we believe that these data represent a good statistical sampling of the activity in the radio spectrum in the Denver metropolitan area. Maximum and minimum activity levels measured in the spectrum are representations of actual activity levels. The mean and median levels provide an unbiased, quantitative estimate of typical received field-strength levels as a function of frequency. While the data presented here can be used to infer the spectrum occupancy, it cannot be used to infer the statistical percentage of time that channels are occupied. Two reasons for this are: 1) the RBW is not always set equal to the channel bandwidth, and 2) some events are measured only intermittently, therefore a complete set of statistics is not available. To obtain data for the latter purpose, a dedicated time-occupancy study similar to the previously reported LMR occupancy study [7], [9] should be performed.

The following figures show results from the spectrum survey. Discussions about each figure follow the data in Section 3.1. Only the allocation information necessary to understanding the signals represented in the figure being discussed is given in the notes column of Table 4. This allocation information is taken from the FCC Online Table of Frequency Allocations [10] and the Federal Spectrum Use Summary [11]. For a complete description of the allocations, the reader is referred to [1], [8], [10], or [11].

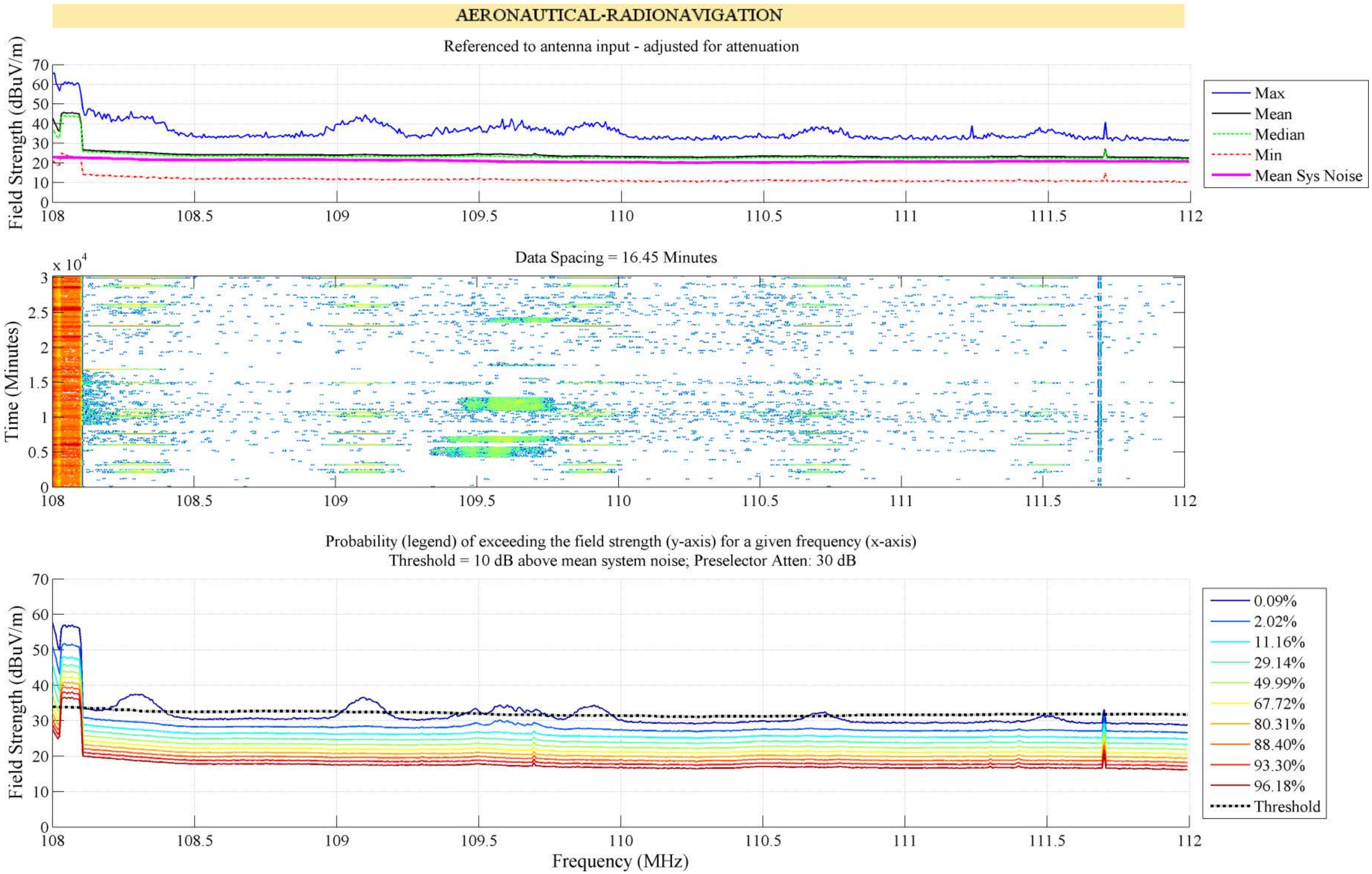

Figure 3. NTIA spectrum survey results from 108 to 112 MHz in Denver, CO, 2011.

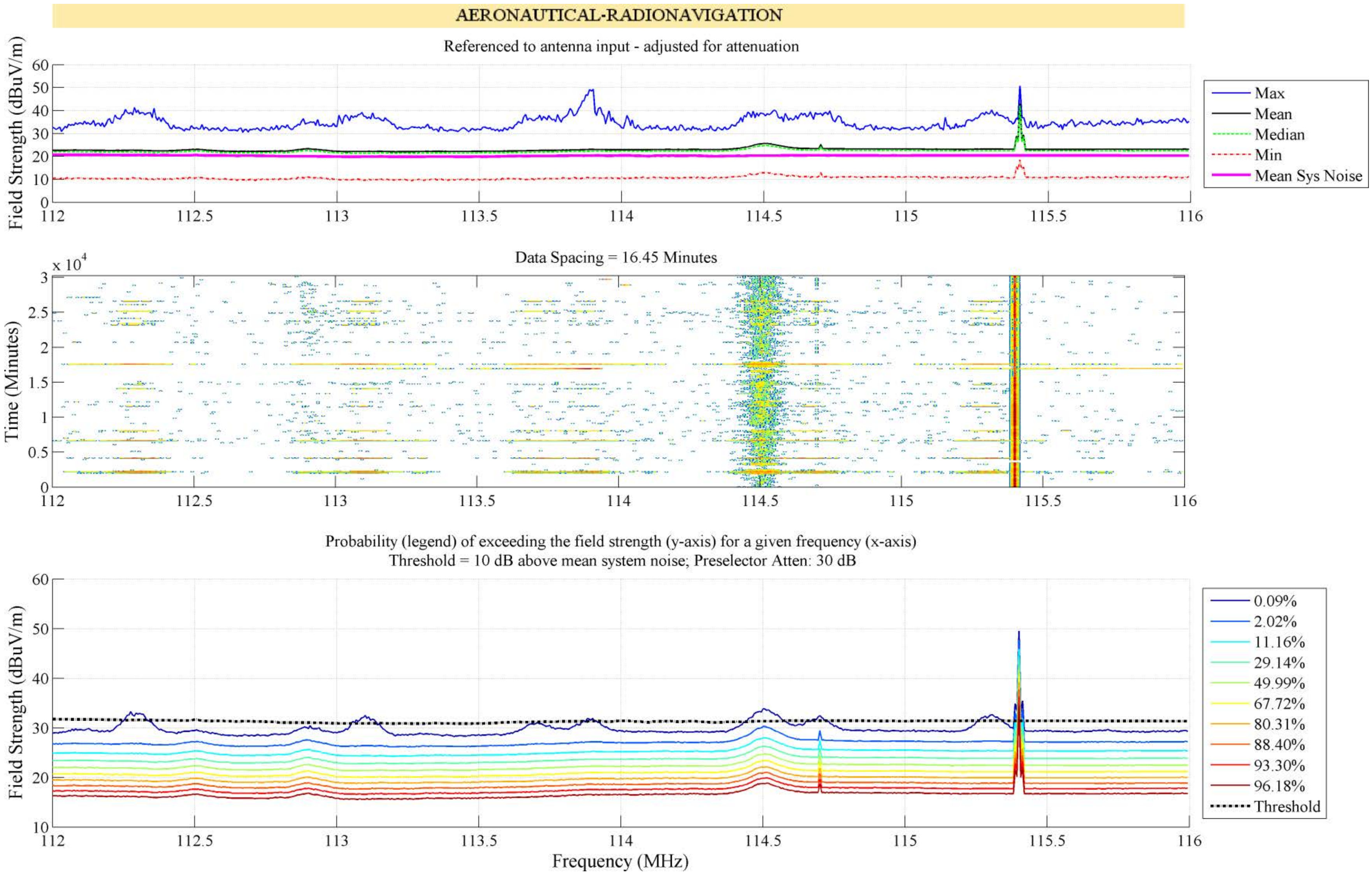

Figure 4. NTIA spectrum survey results from 112 to 116 MHz in Denver, CO, 2011.

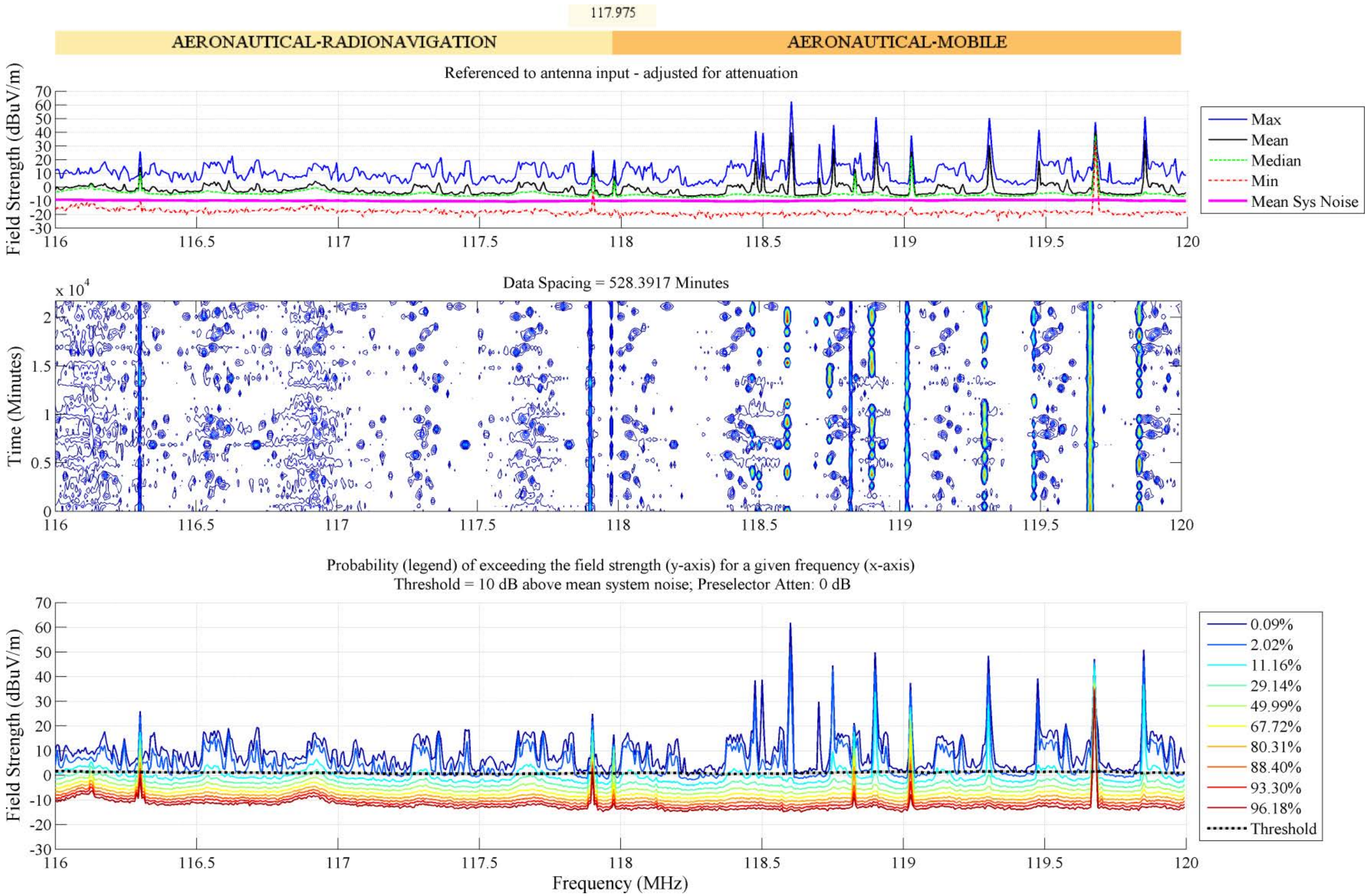

Figure 5. NTIA spectrum survey results from 116 to 120 MHz in Denver, CO, 2011.

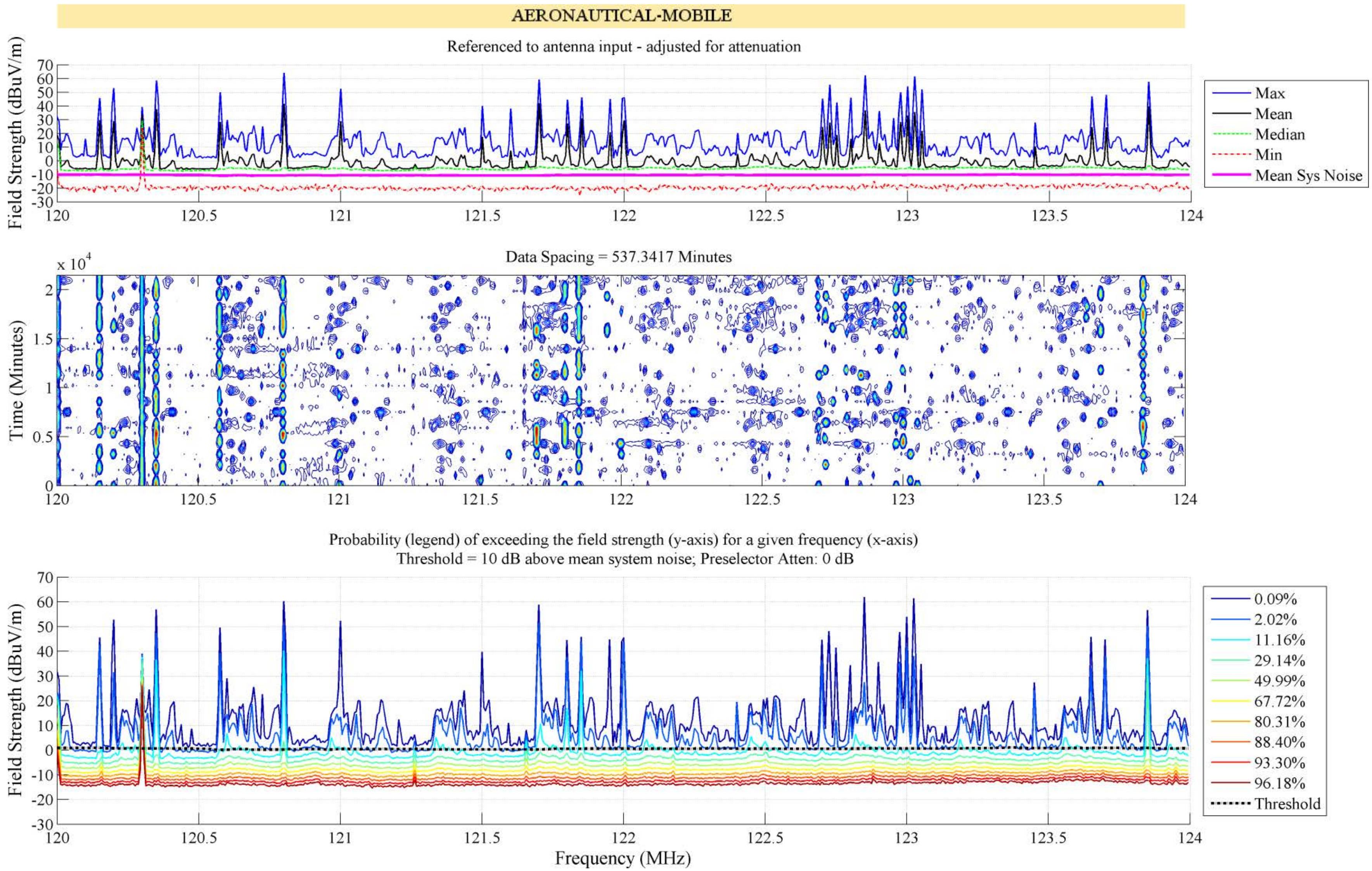

Figure 6. NTIA spectrum survey results from 120 to 124 MHz in Denver, CO, 2011.

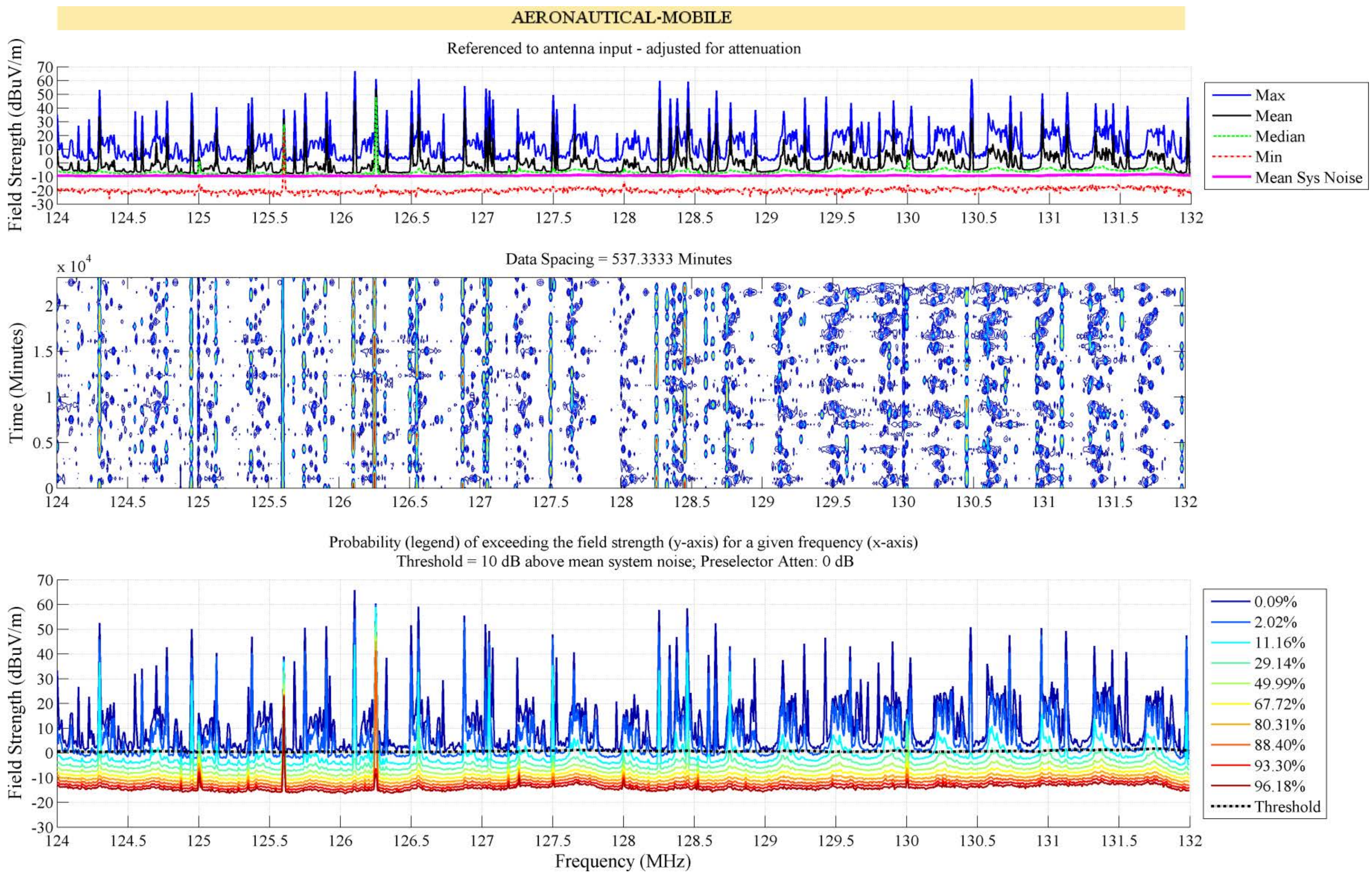

Figure 7. NTIA spectrum survey results from 124 to 132 MHz in Denver, CO, 2011.

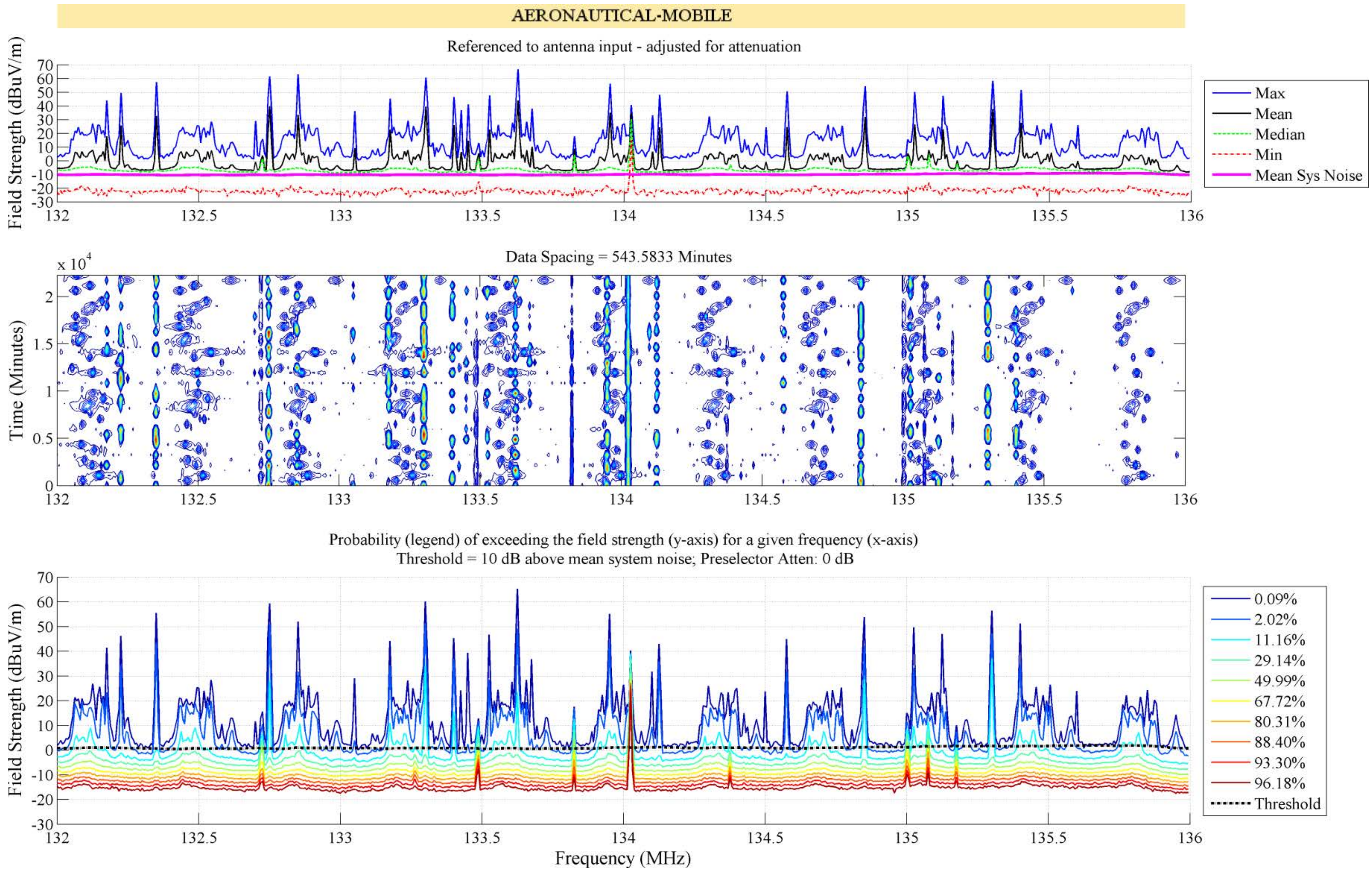

Figure 8. NTIA spectrum survey results from 132 to 136 MHz in Denver, CO, 2011.

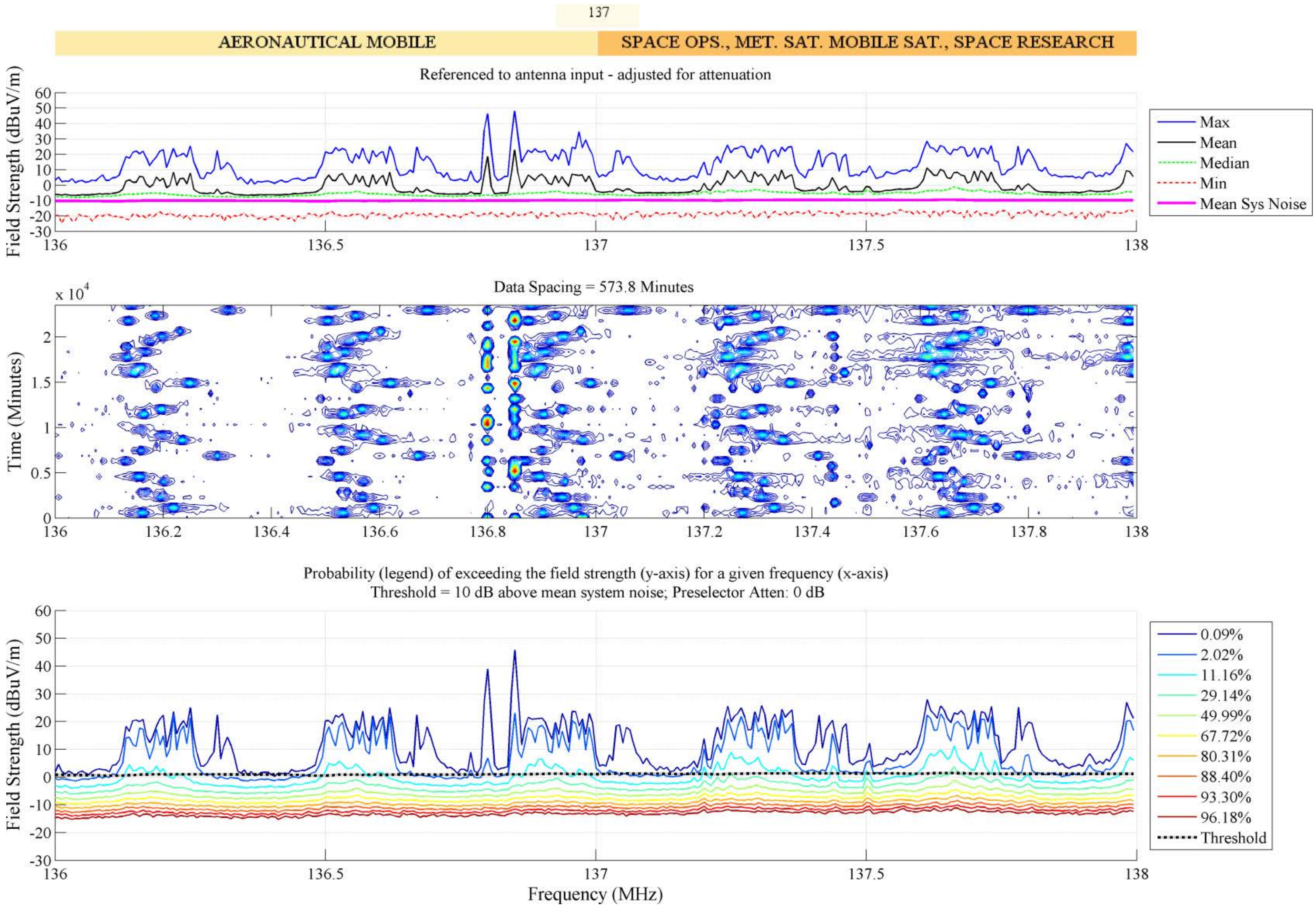

Figure 9. NTIA spectrum survey results from 136 to 138 MHz in Denver, CO, 2011.

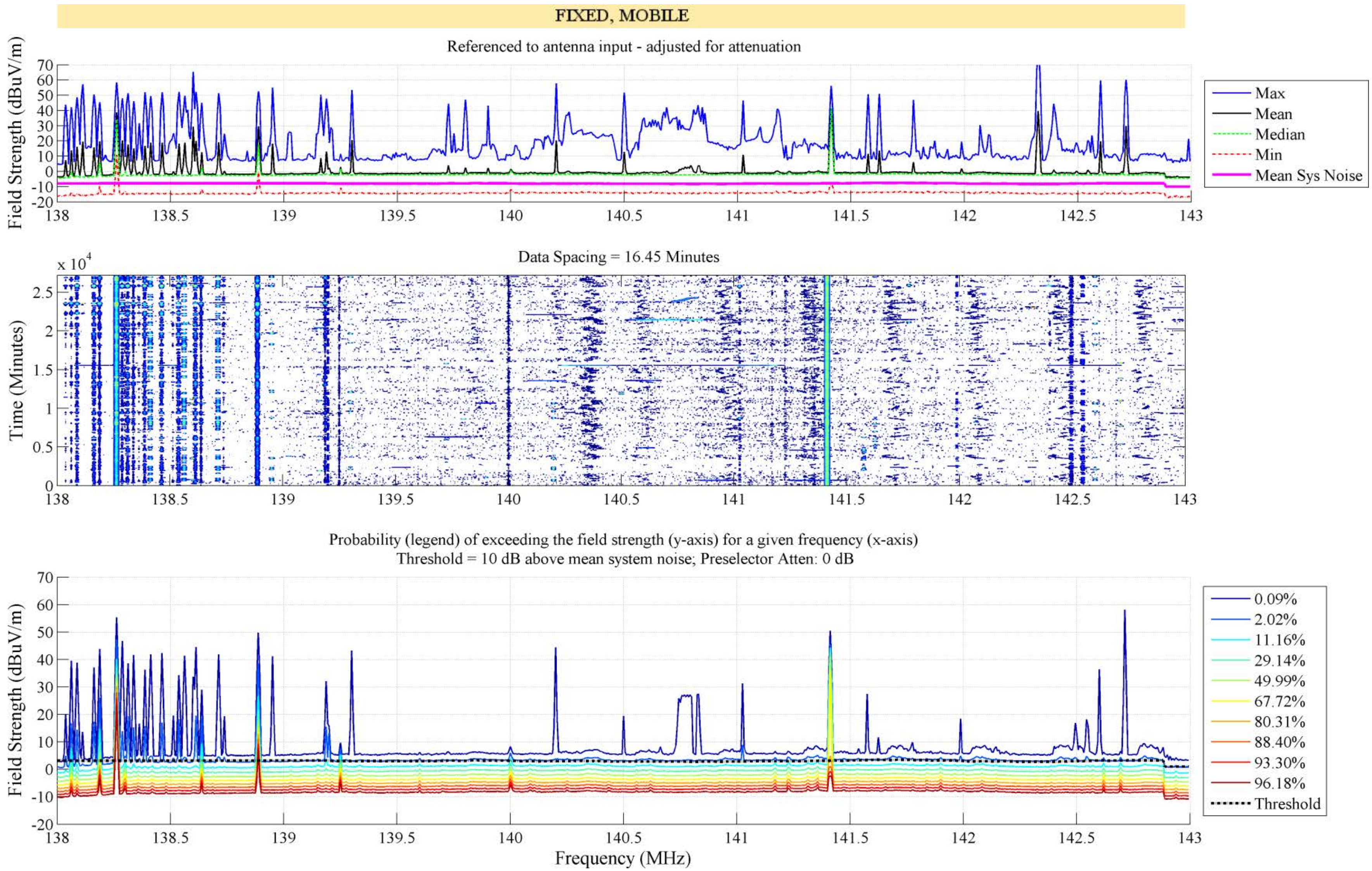

Figure 10. NTIA spectrum survey results from 138 to 143 MHz in Denver, CO, 2011.

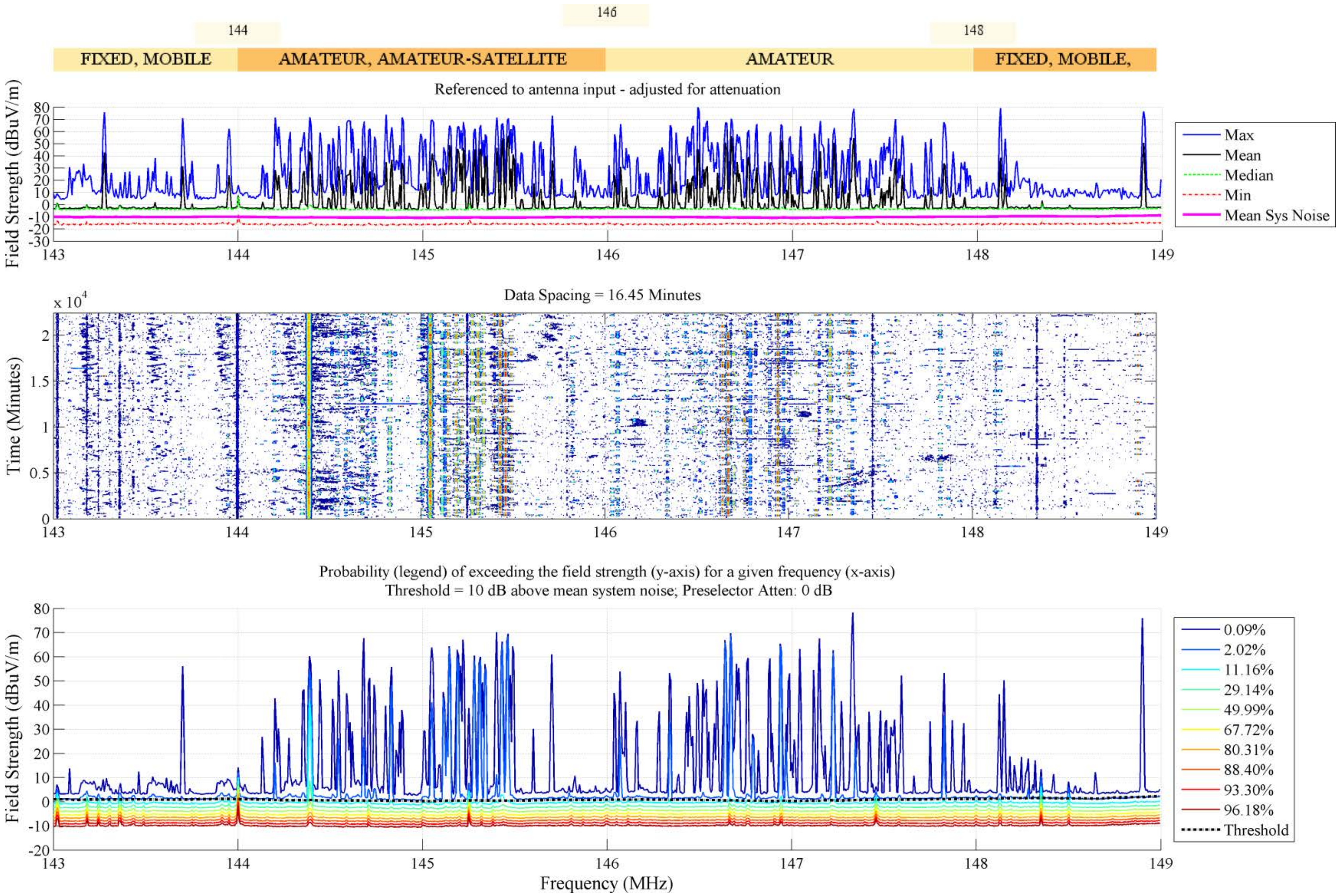

Figure 11. NTIA spectrum survey results from 143 to 149 MHz in Denver, CO, 2011.

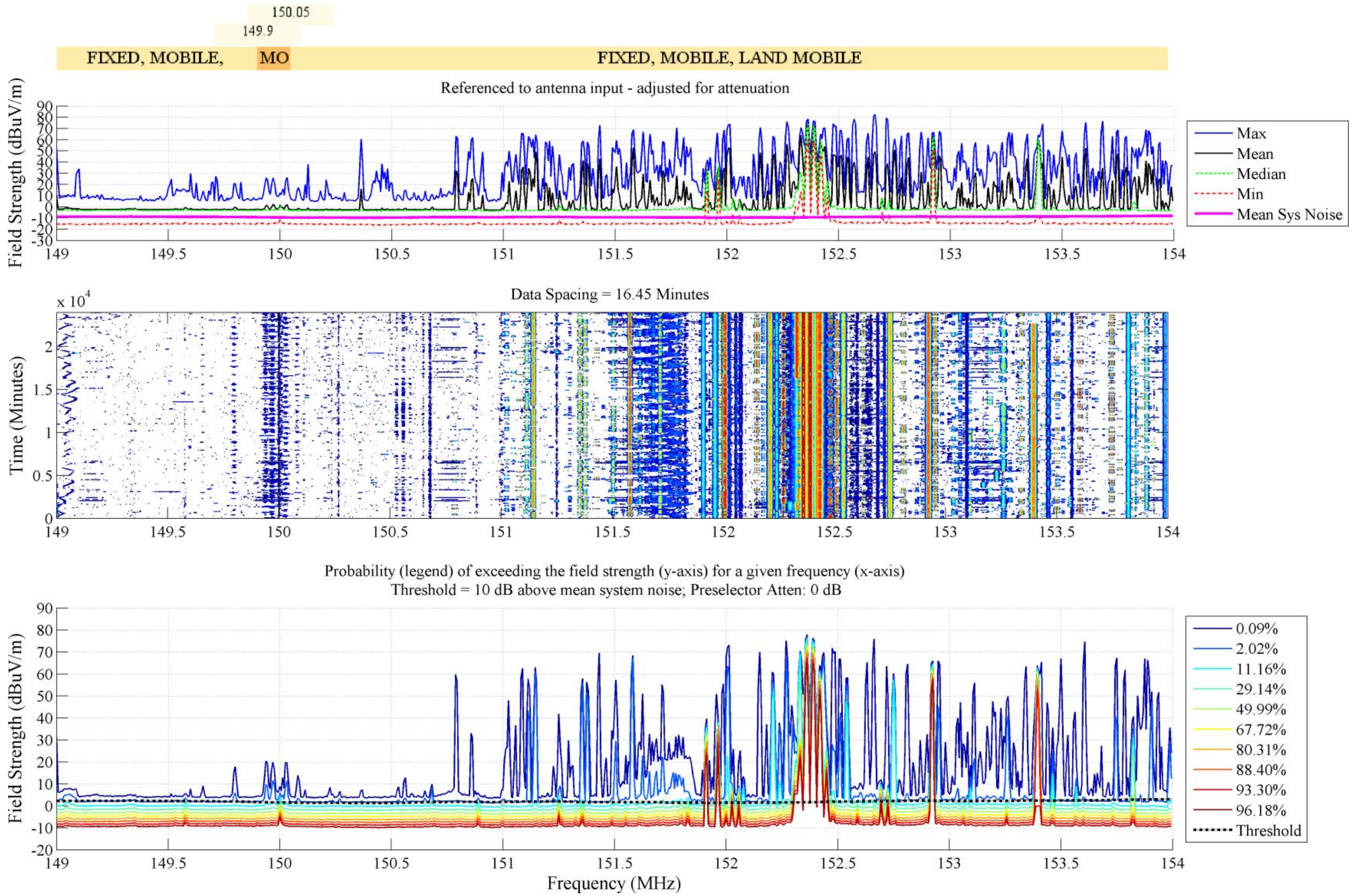

Figure 12. NTIA spectrum survey results from 149 to 154 MHz in Denver, CO, 2011.

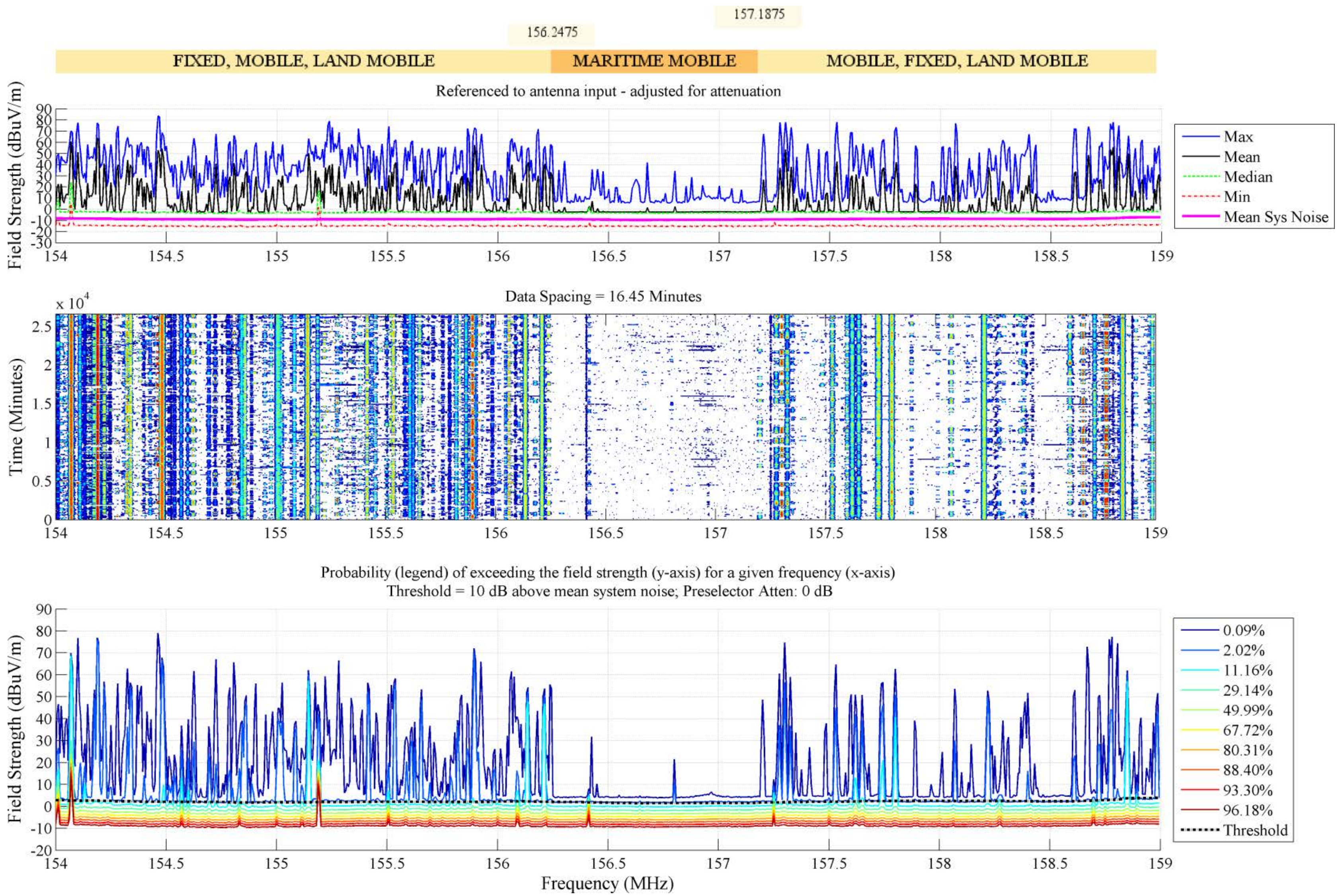

Figure 13. NTIA spectrum survey results from 154 to 159 MHz in Denver, CO, 2011.

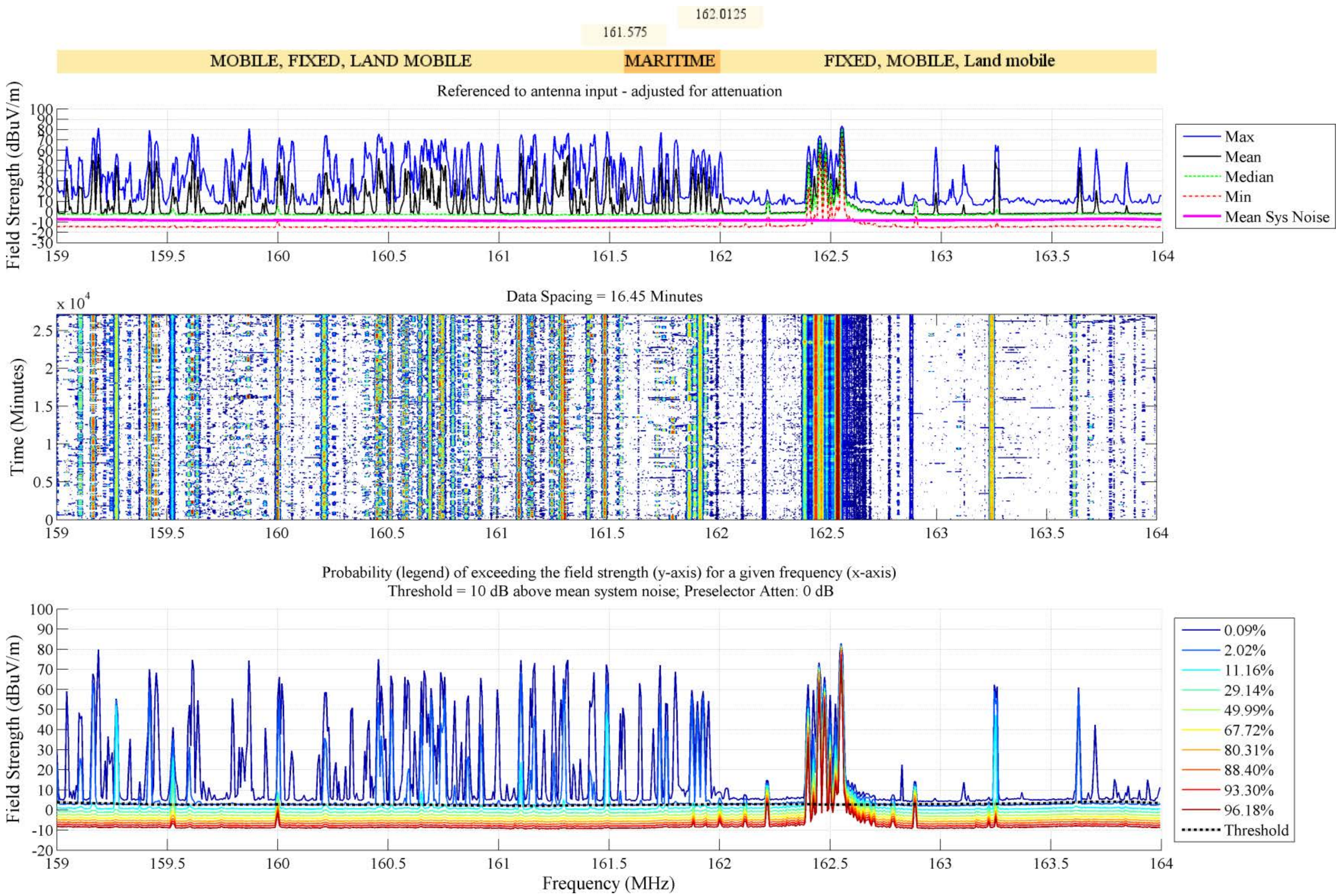

Figure 14. NTIA spectrum survey results from 159 to 164 MHz in Denver, CO, 2011.

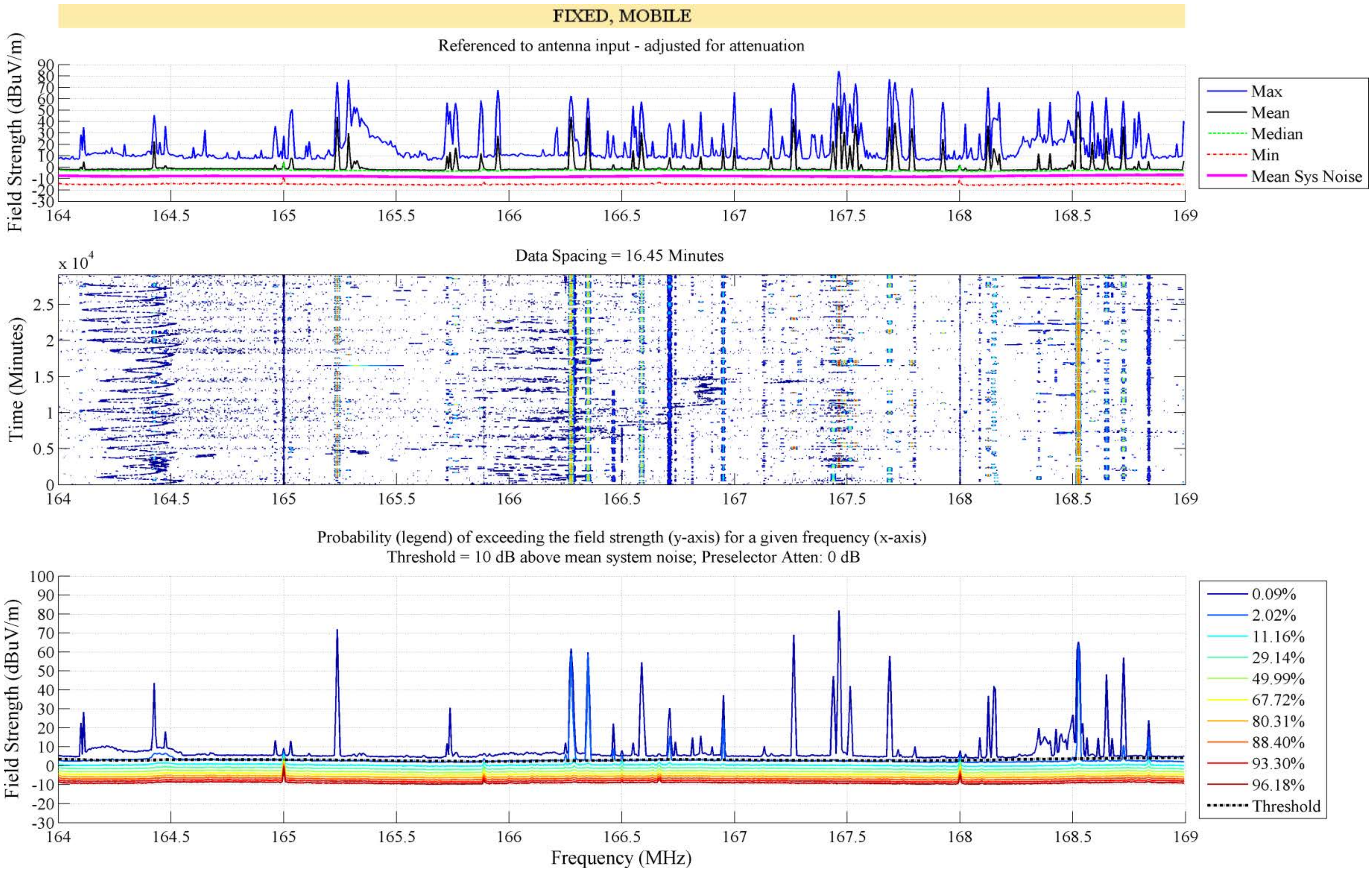

Figure 15. NTIA spectrum survey results from 164 to 169 MHz in Denver, CO, 2011.

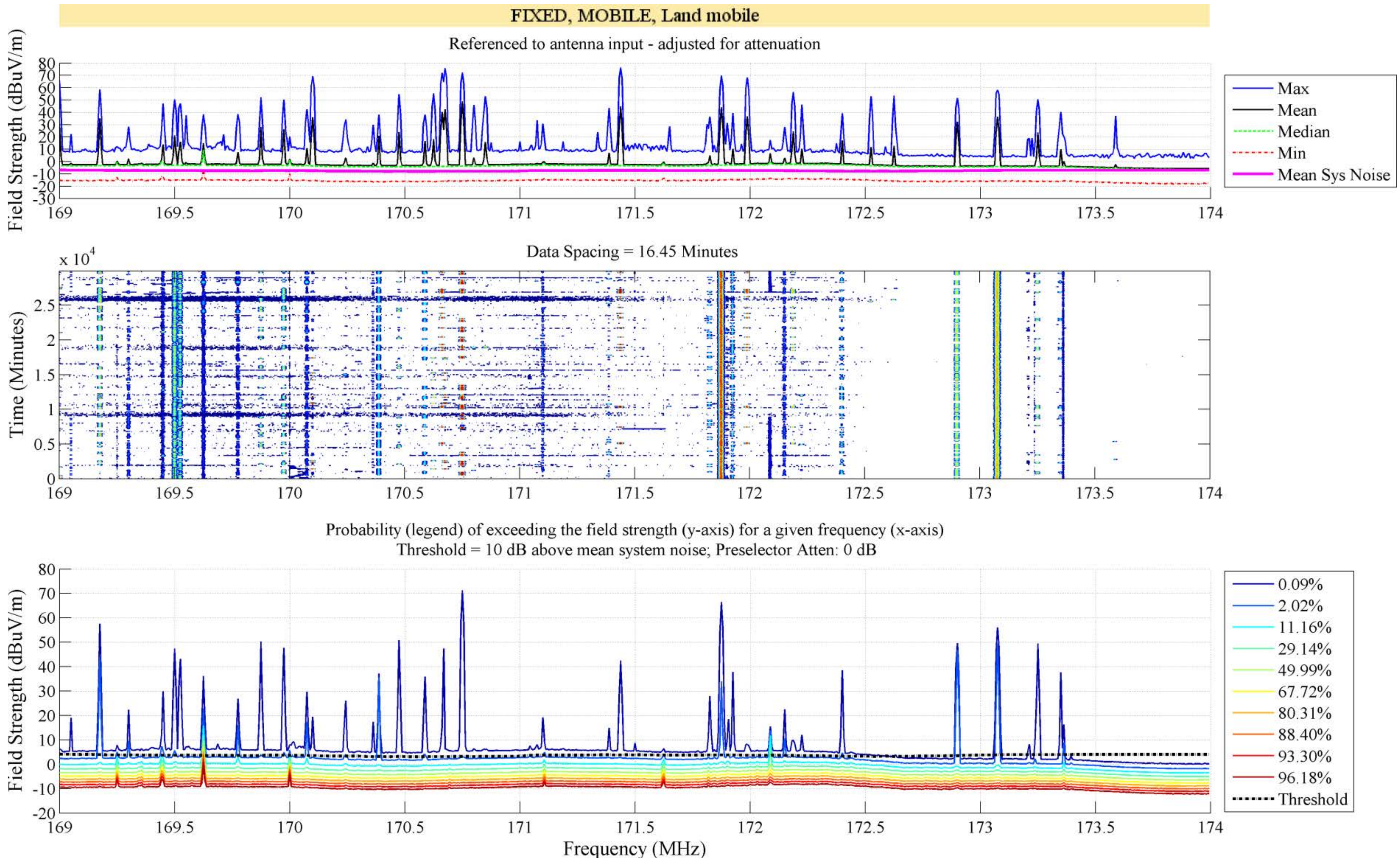

Figure 16. NTIA spectrum survey results from 169 to 174 MHz in Denver, CO, 2011.

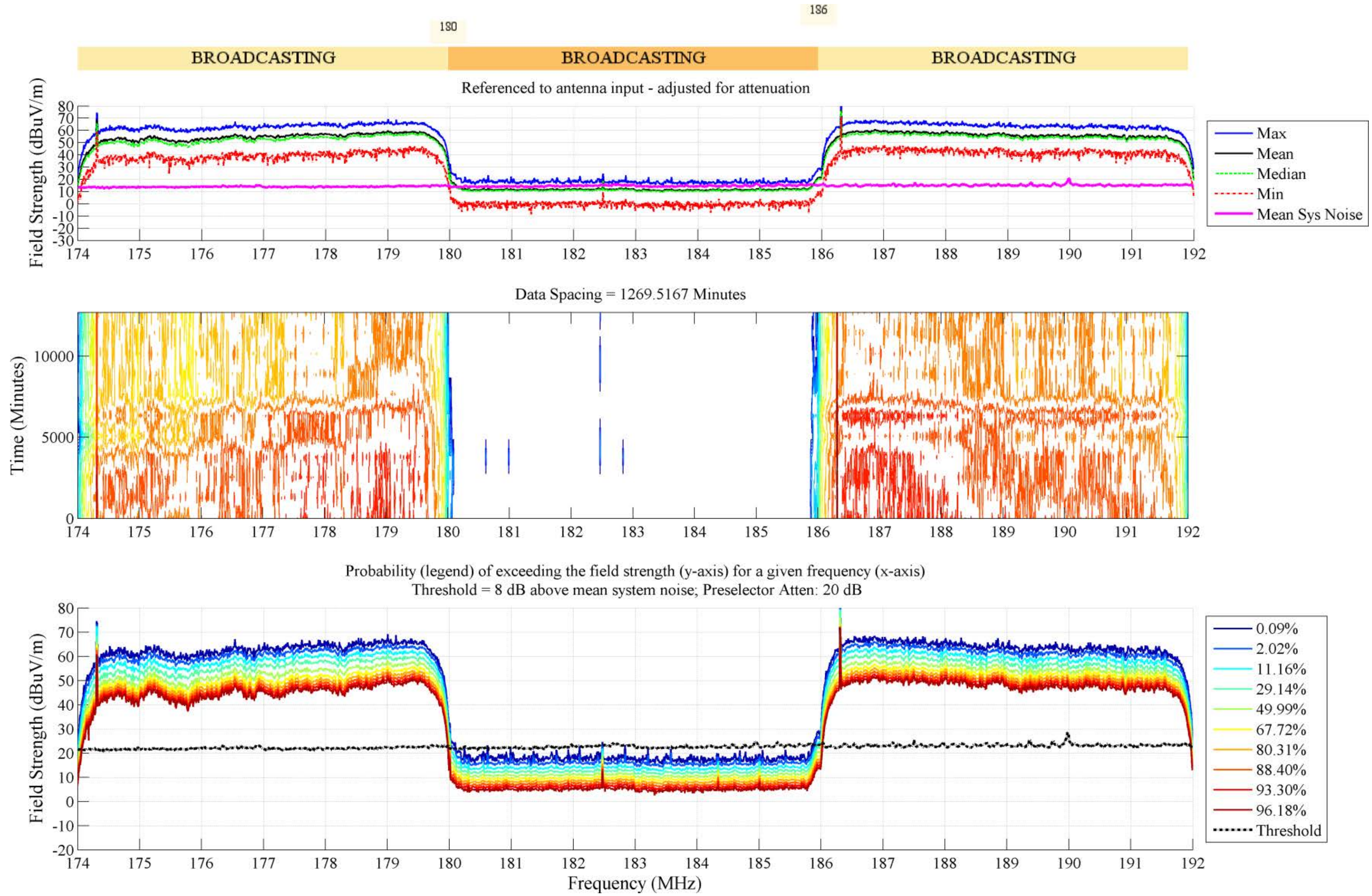

Figure 17. NTIA spectrum survey results from 174 to 192 MHz in Denver, CO, 2011.

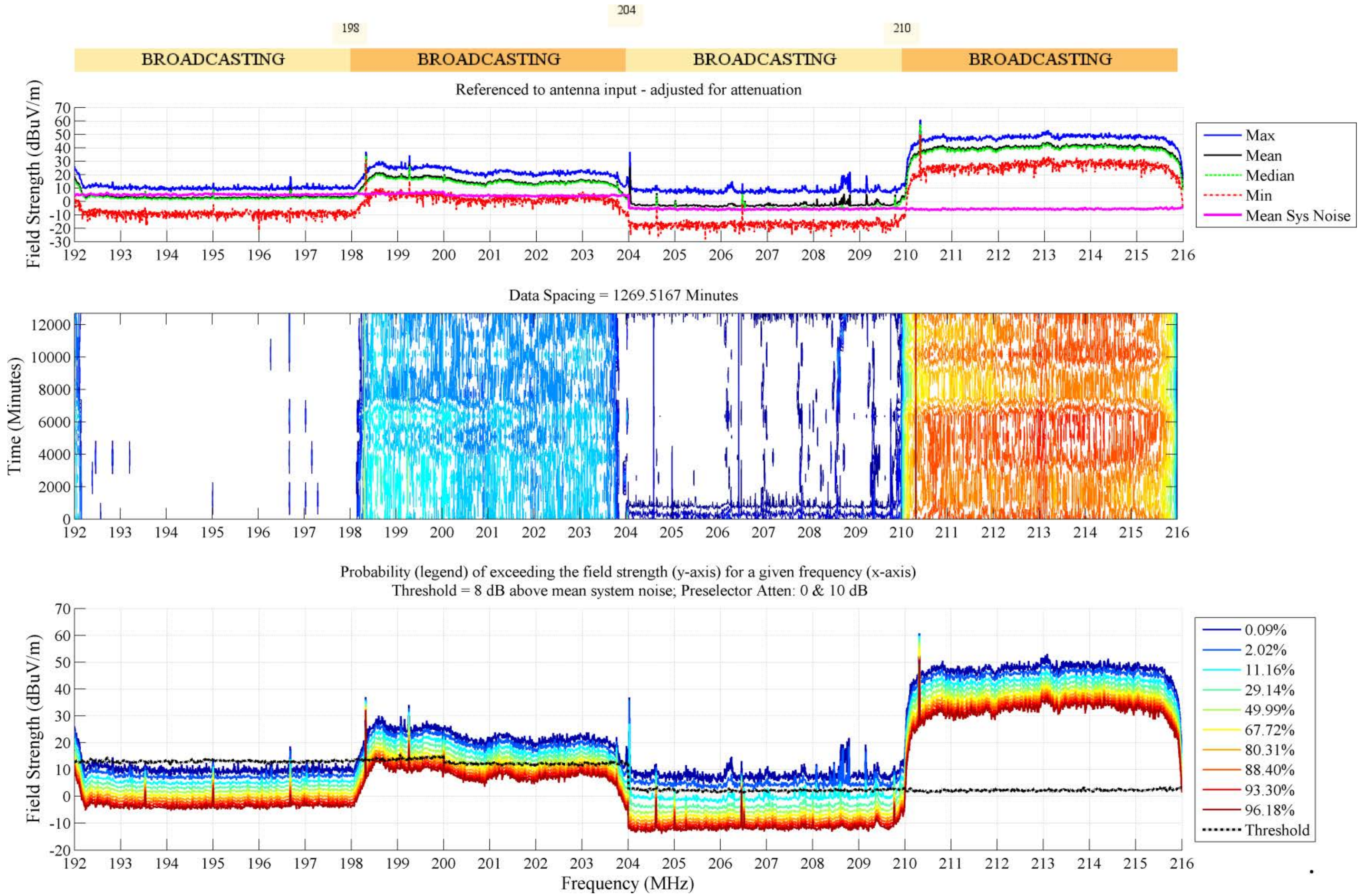

Figure 18. NTIA spectrum survey results from 192 to 216 MHz in Denver, CO, 2011.

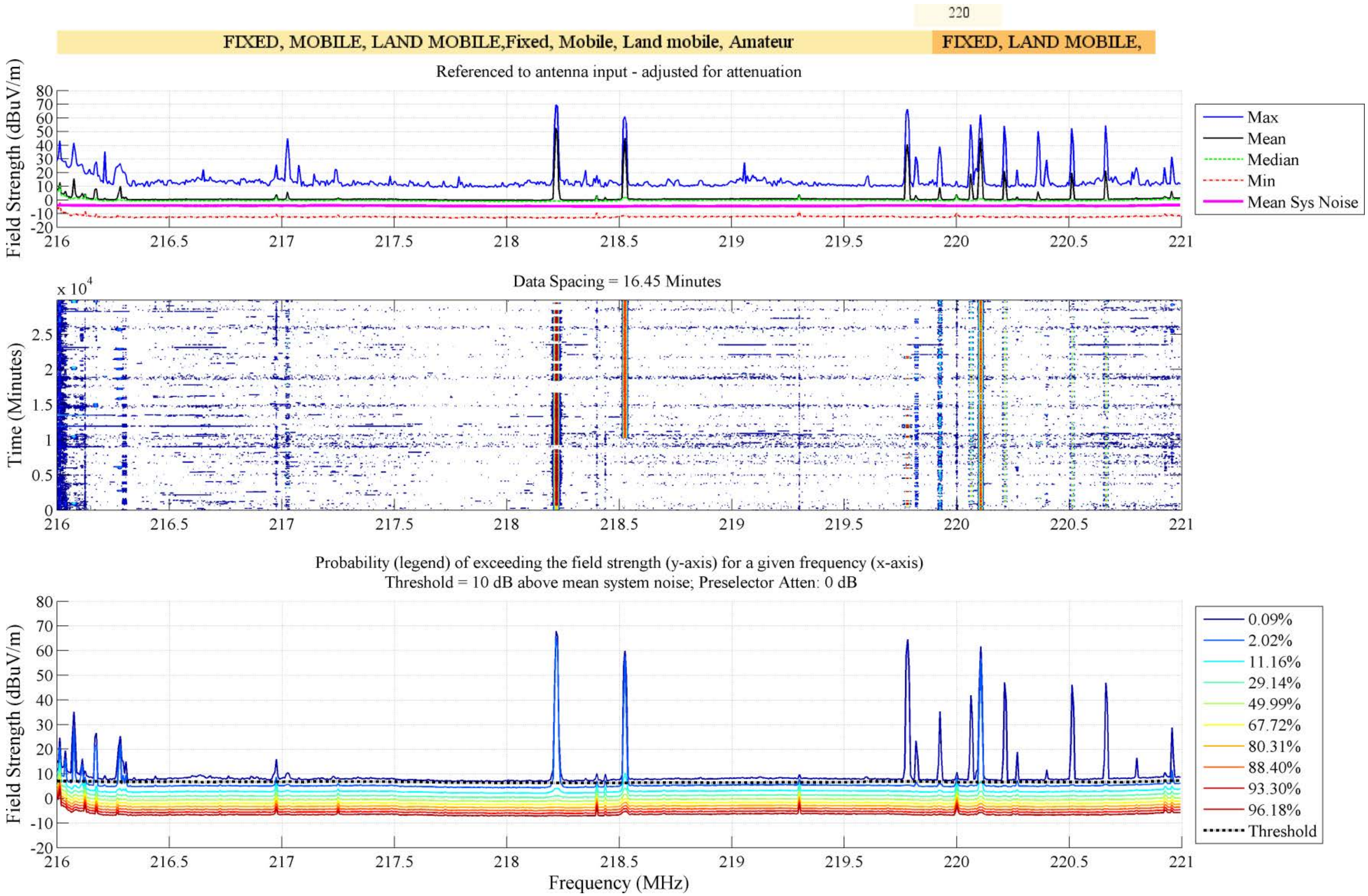

Figure 19. NTIA spectrum survey results from 216 to 221 MHz in Denver, CO, 2011.

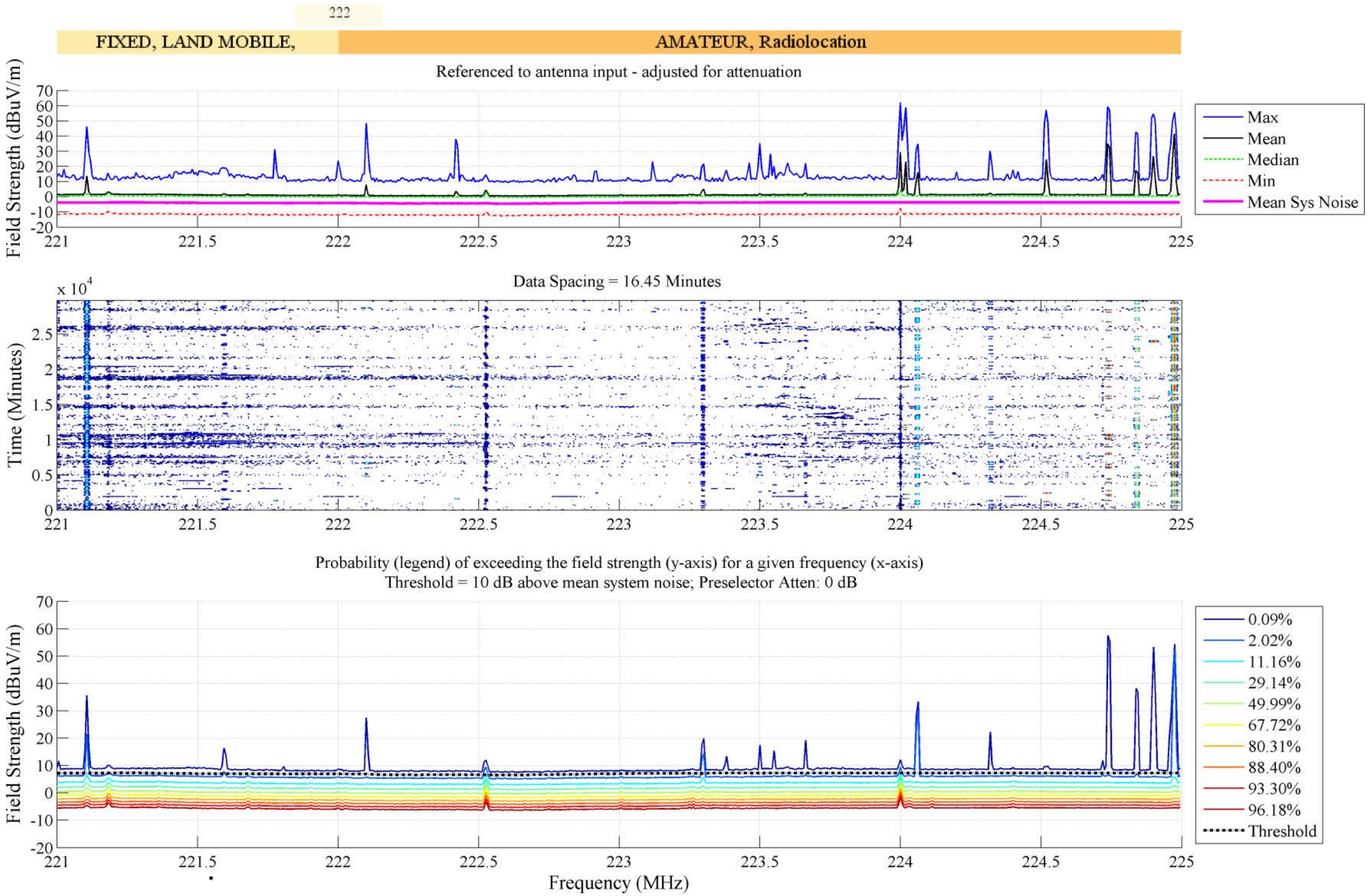

Figure 20. NTIA spectrum survey results from 221 to 225 MHz in Denver, CO, 2011.

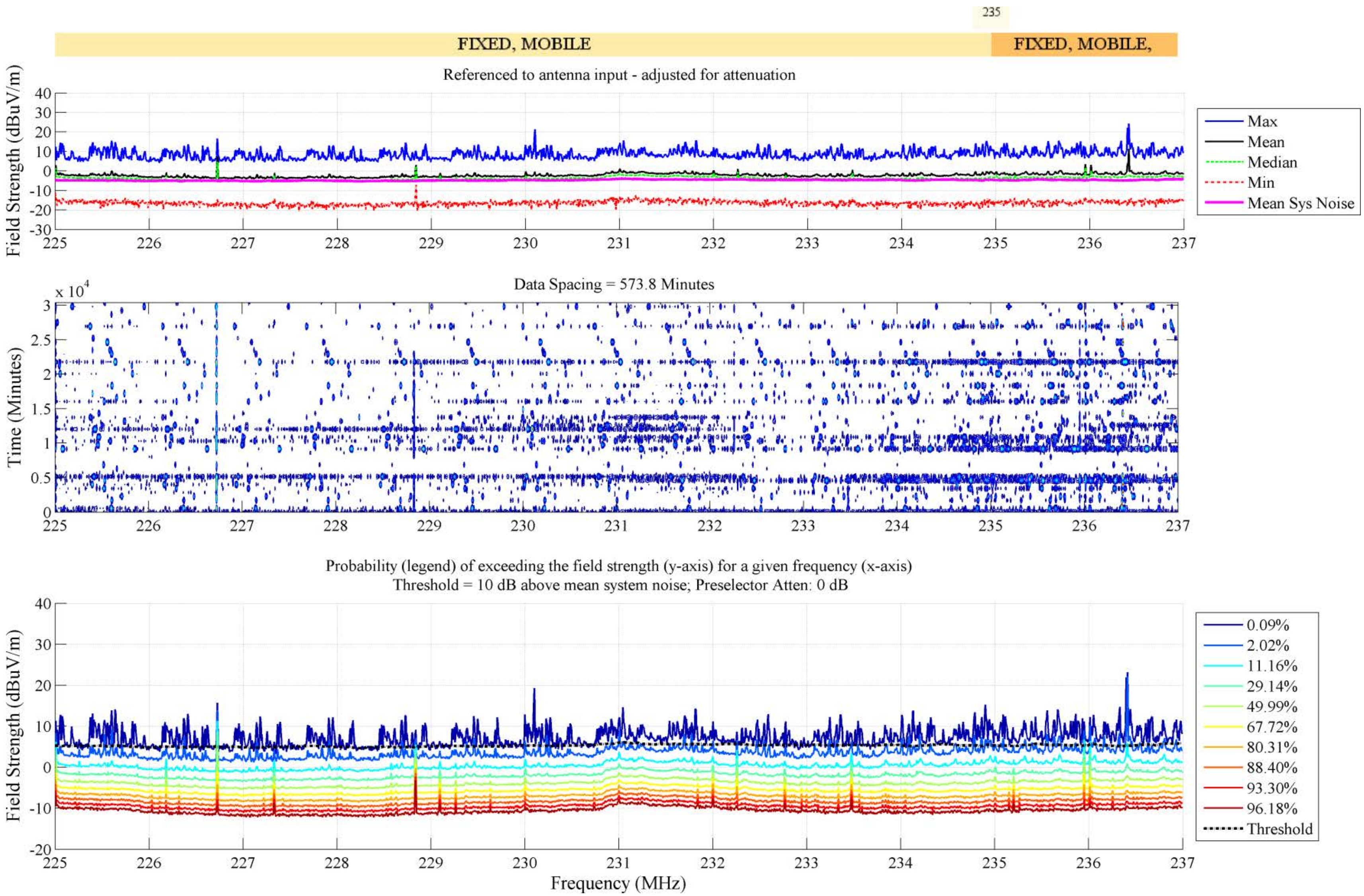

Figure 21. NTIA spectrum survey results from 225 to 237 MHz in Denver, CO, 2011.

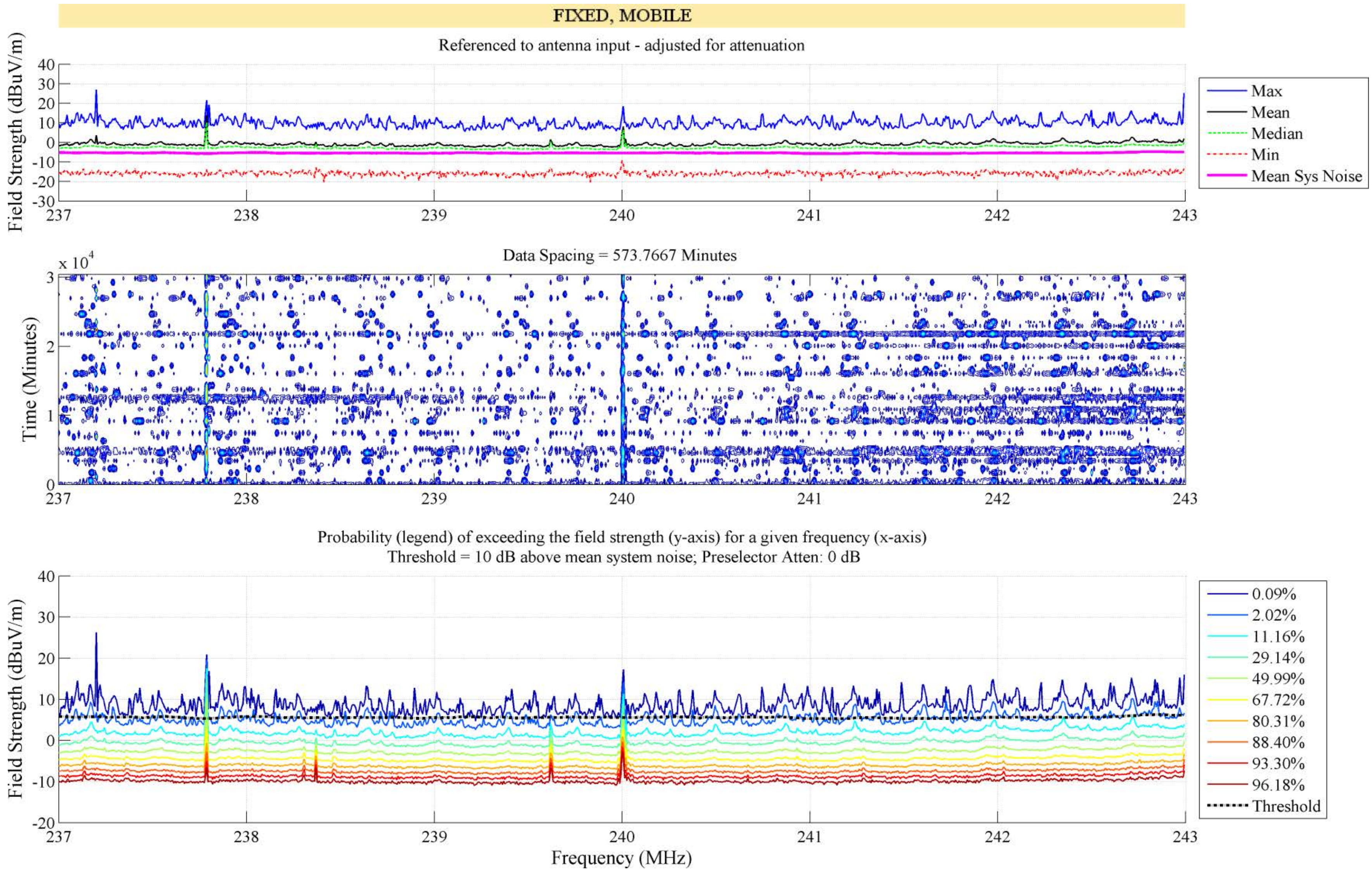

Figure 22. NTIA spectrum survey results from 237 to 243 MHz in Denver, CO, 2011.

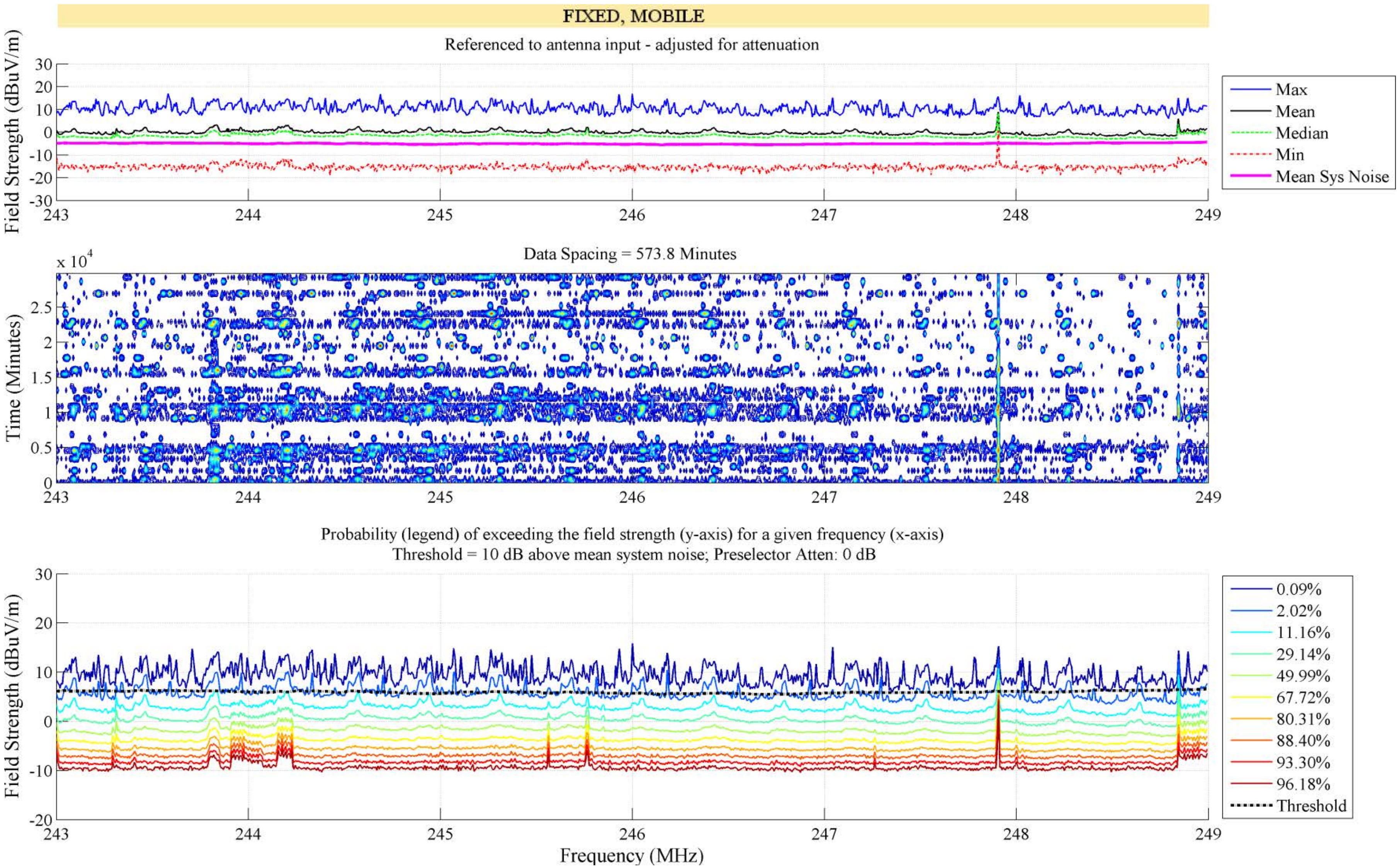

Figure 23. NTIA spectrum survey results from 243 to 249 MHz in Denver, CO, 2011.

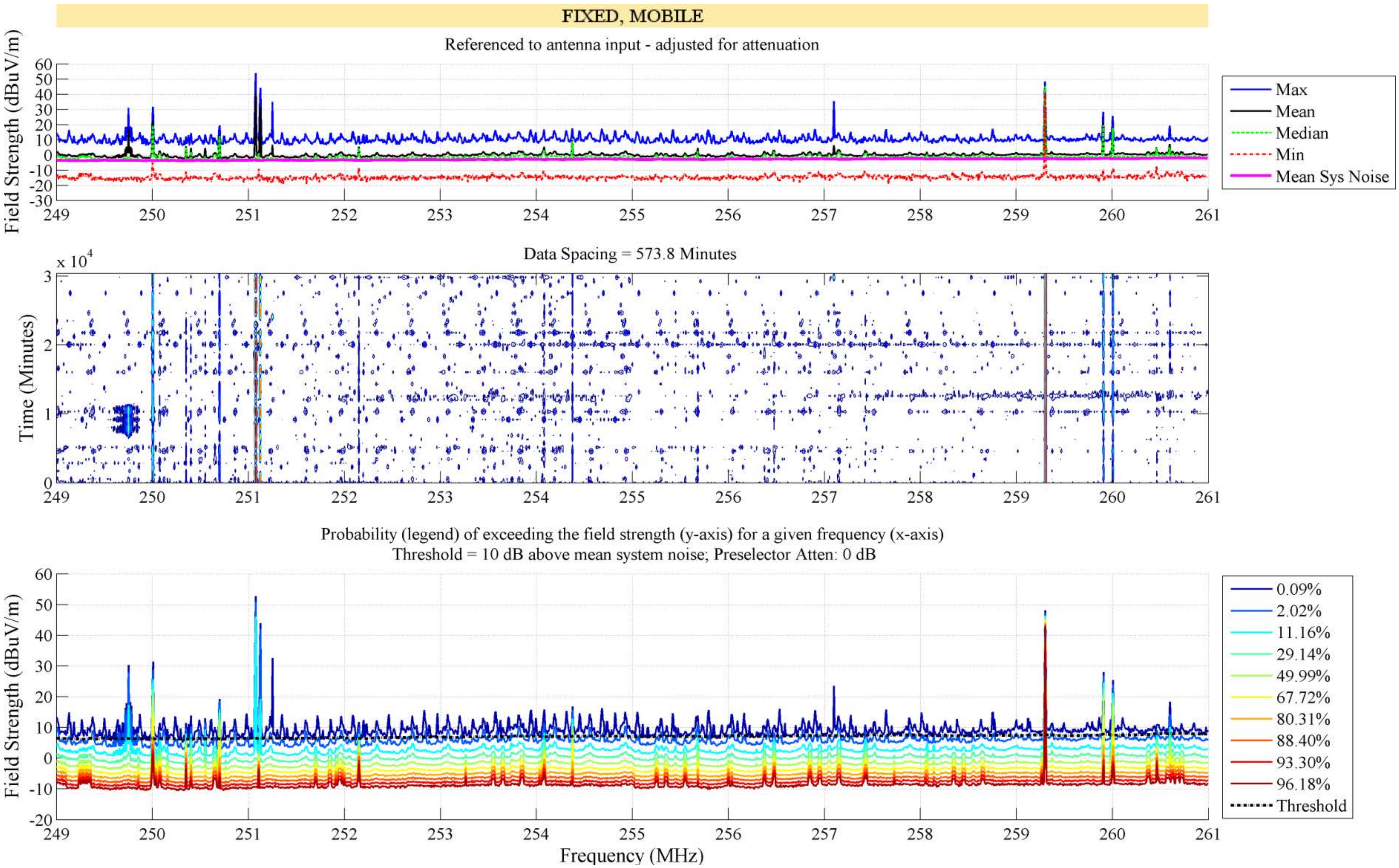

Figure 24. NTIA spectrum survey results from 249 to 261 MHz in Denver, CO, 2011.

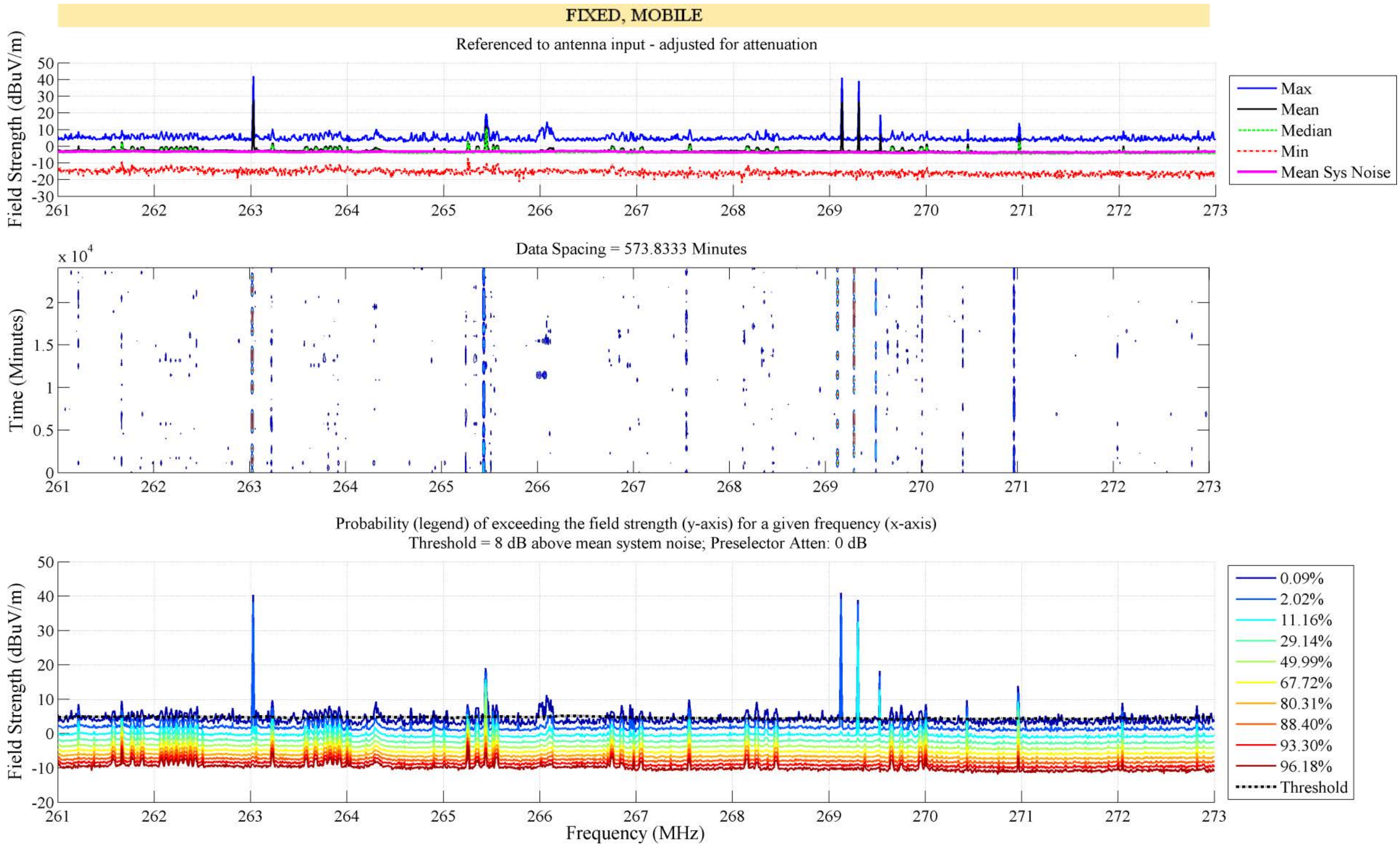

Figure 25. NTIA spectrum survey results from 261 to 273 MHz in Denver, CO, 2011.

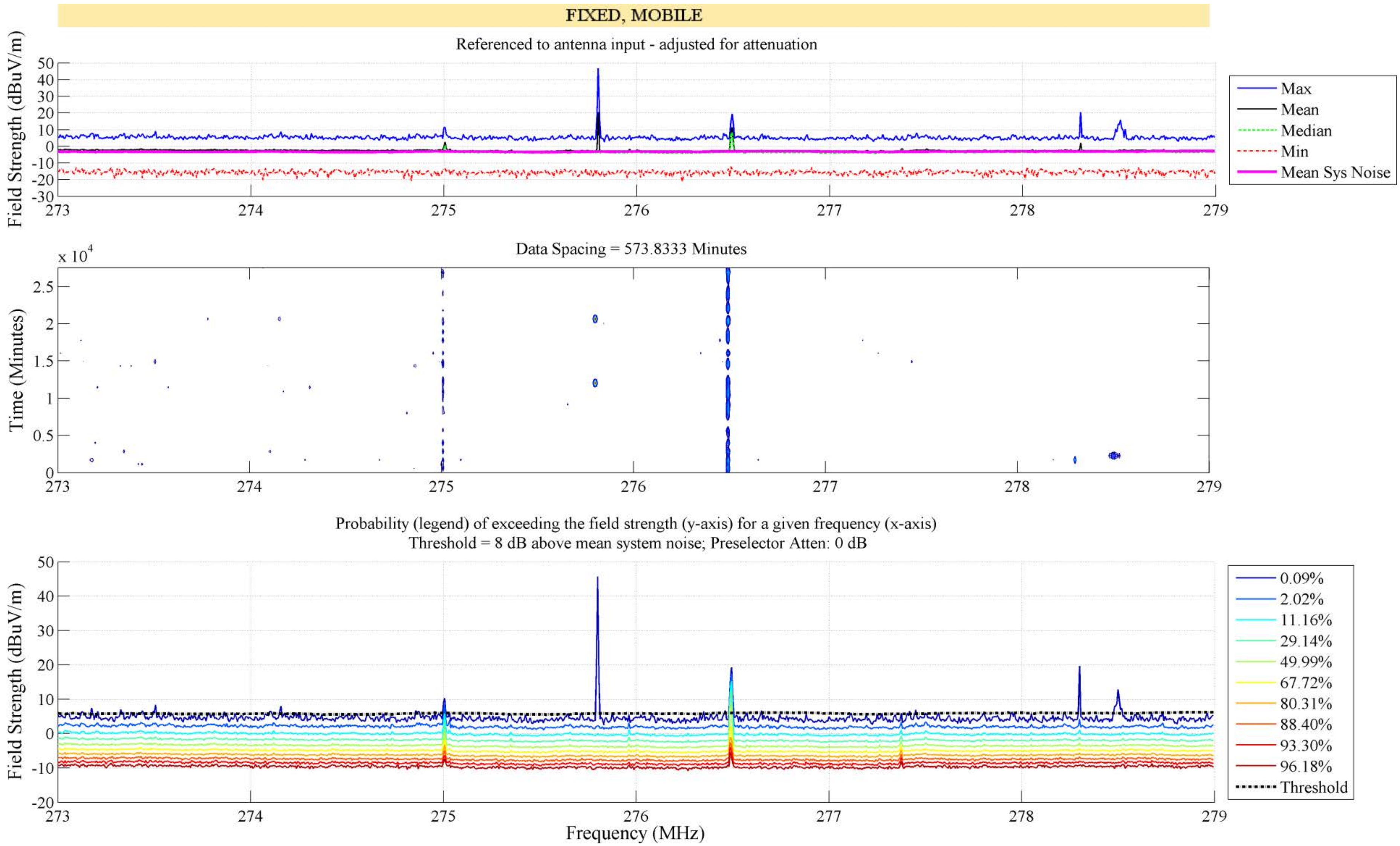

Figure 26. NTIA spectrum survey results from 273 to 279 MHz in Denver, CO, 2011.

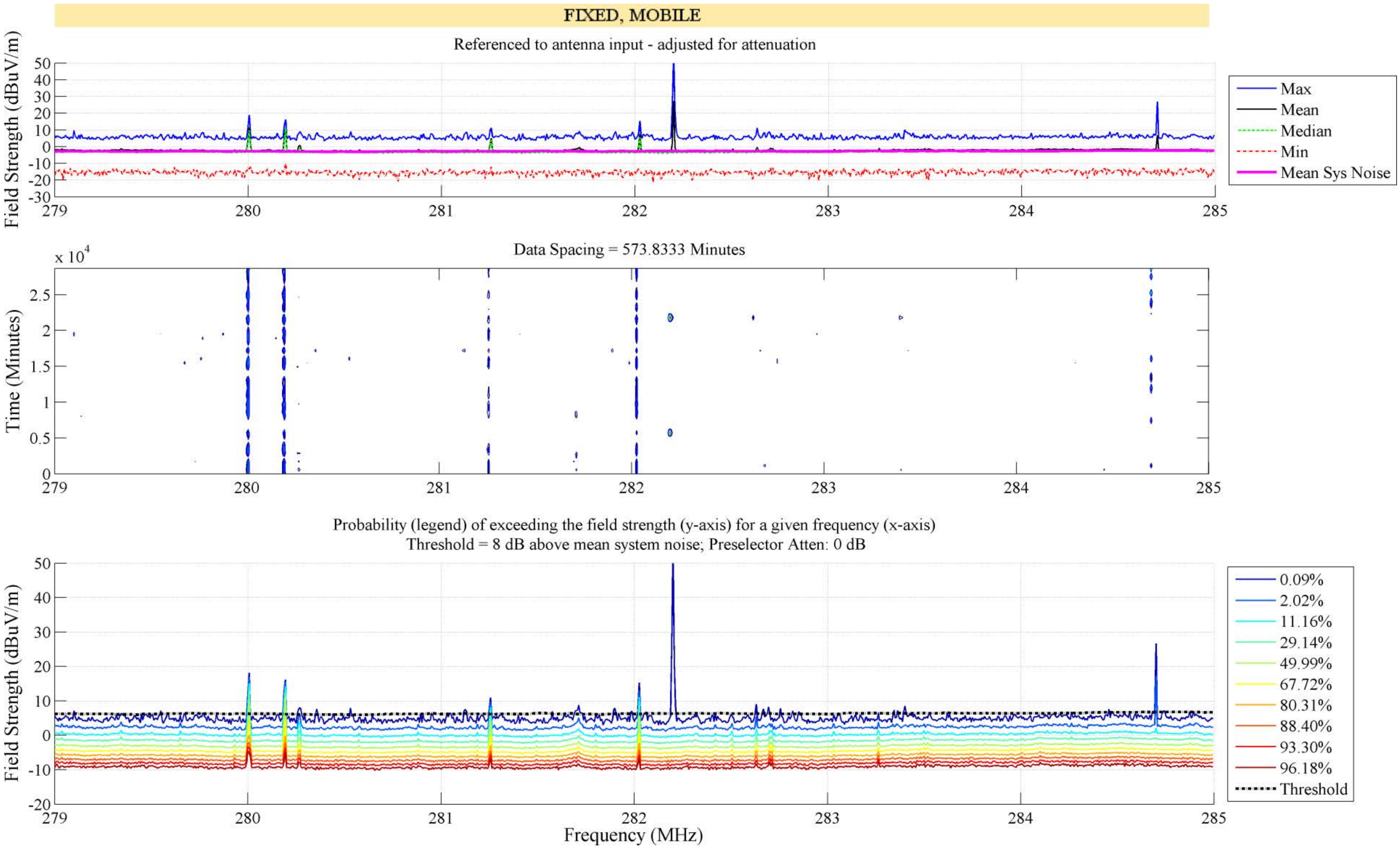

Figure 27. NTIA spectrum survey results from 279 to 285 MHz in Denver, CO, 2011.

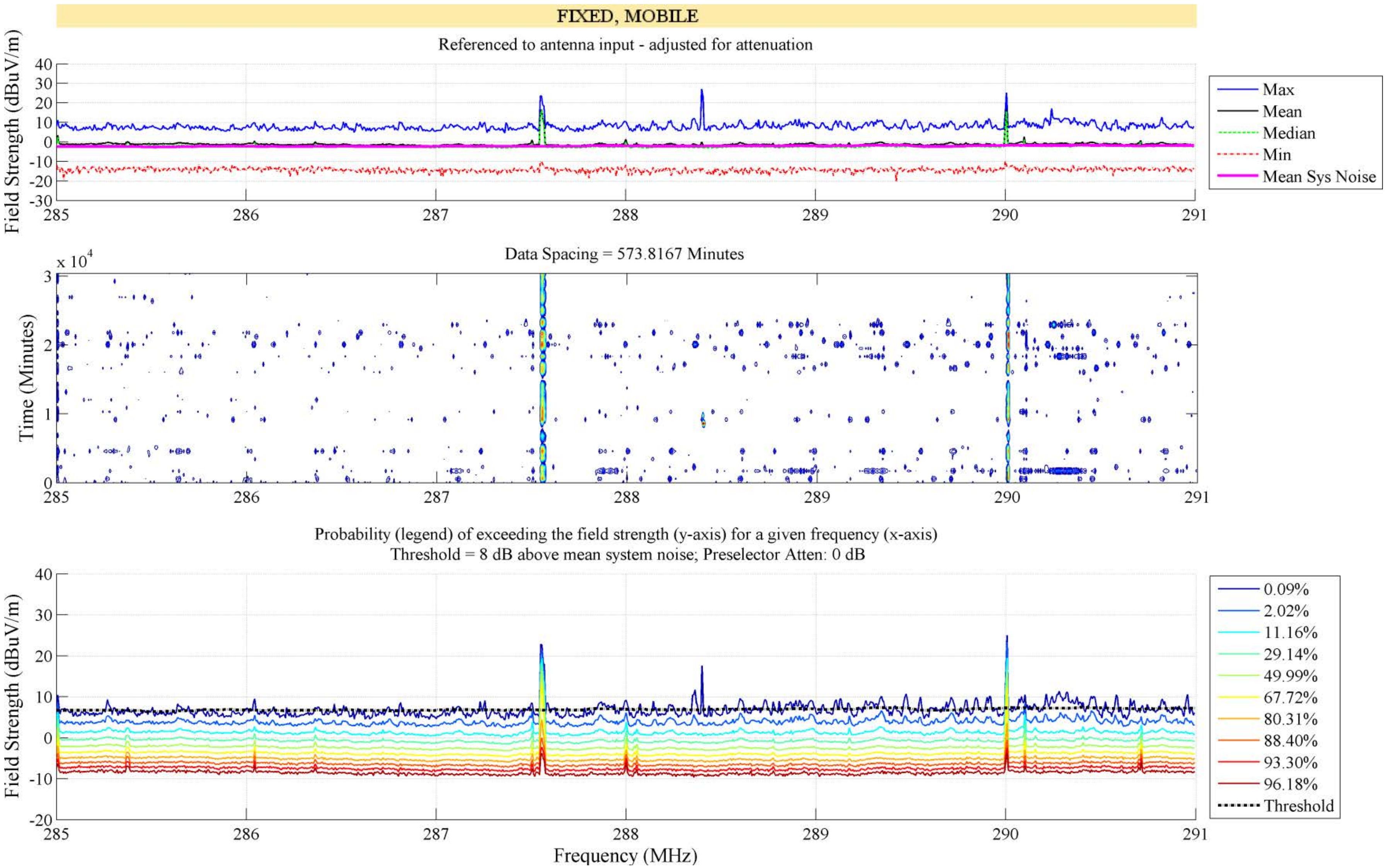

Figure 28. NTIA spectrum survey results from 285 to 291 MHz in Denver, CO, 2011.

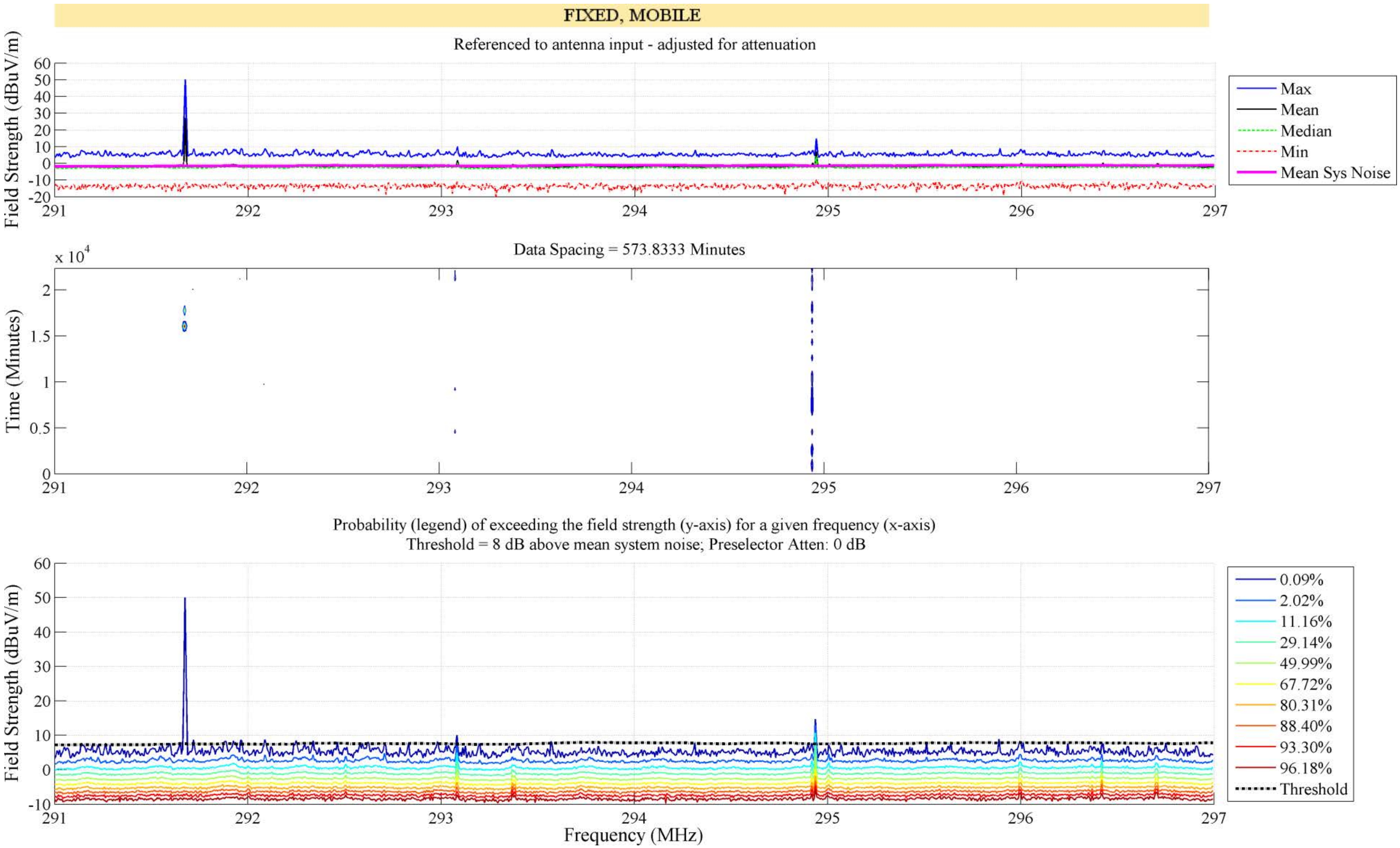

Figure 29. NTIA spectrum survey results from 291 to 297 MHz in Denver, CO, 2011.

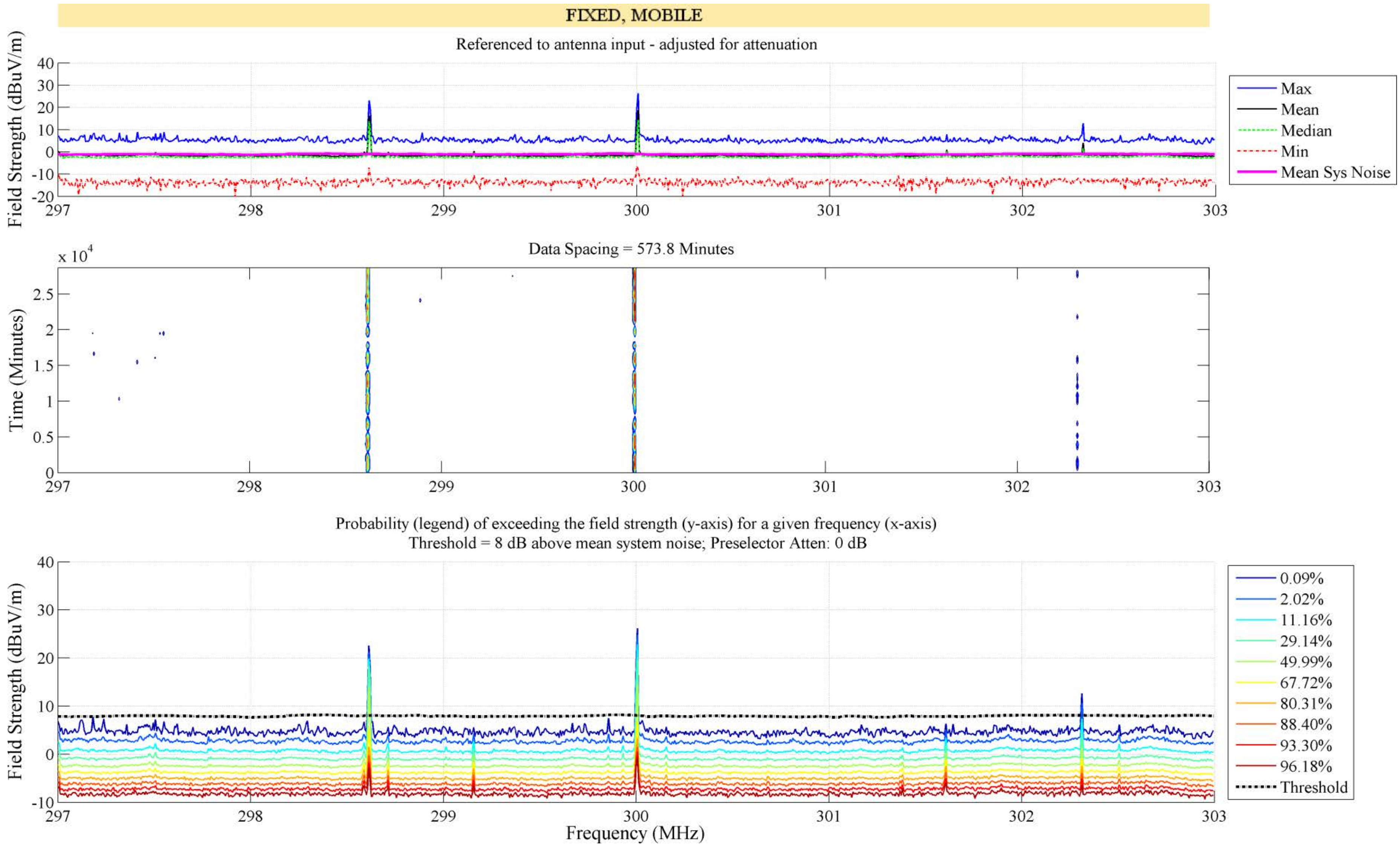

Figure 30. NTIA spectrum survey results from 297 to 303 MHz in Denver, CO, 2011.

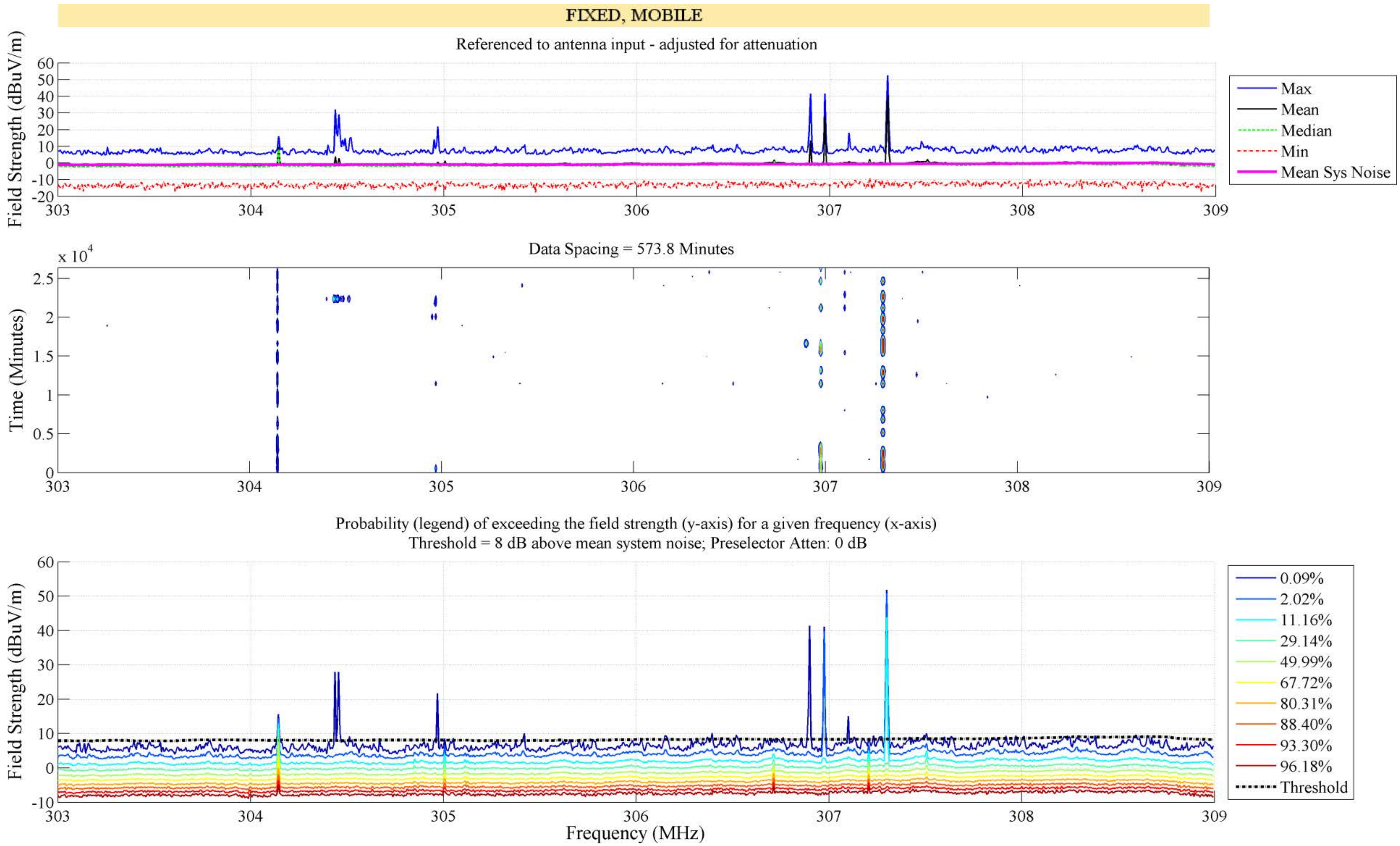

Figure 31.NTIA spectrum survey results from 303 to 309 MHz in Denver, CO, 2011.

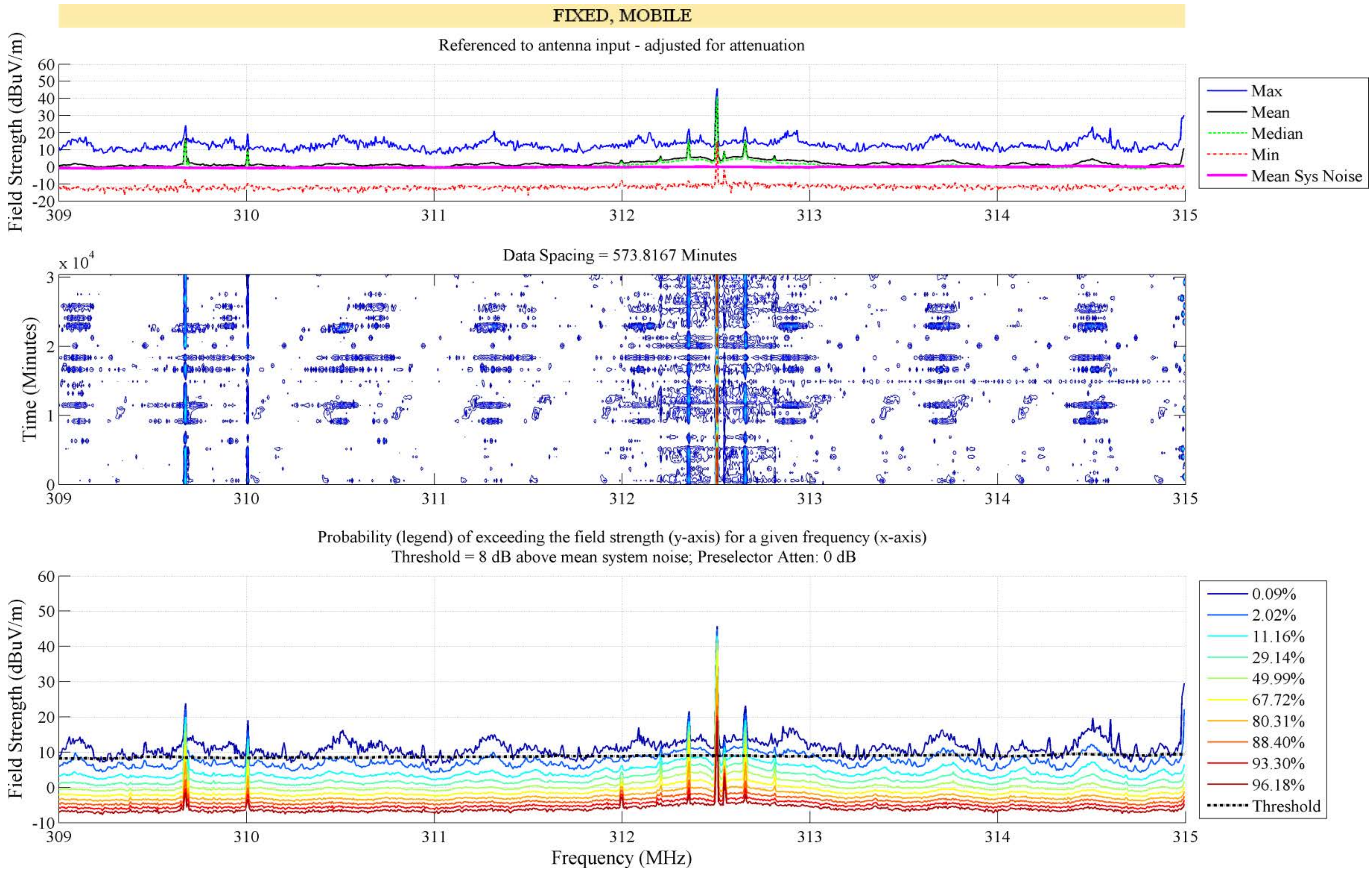

Figure 32. NTIA spectrum survey results from 309 to 315 MHz in Denver, CO, 2011.

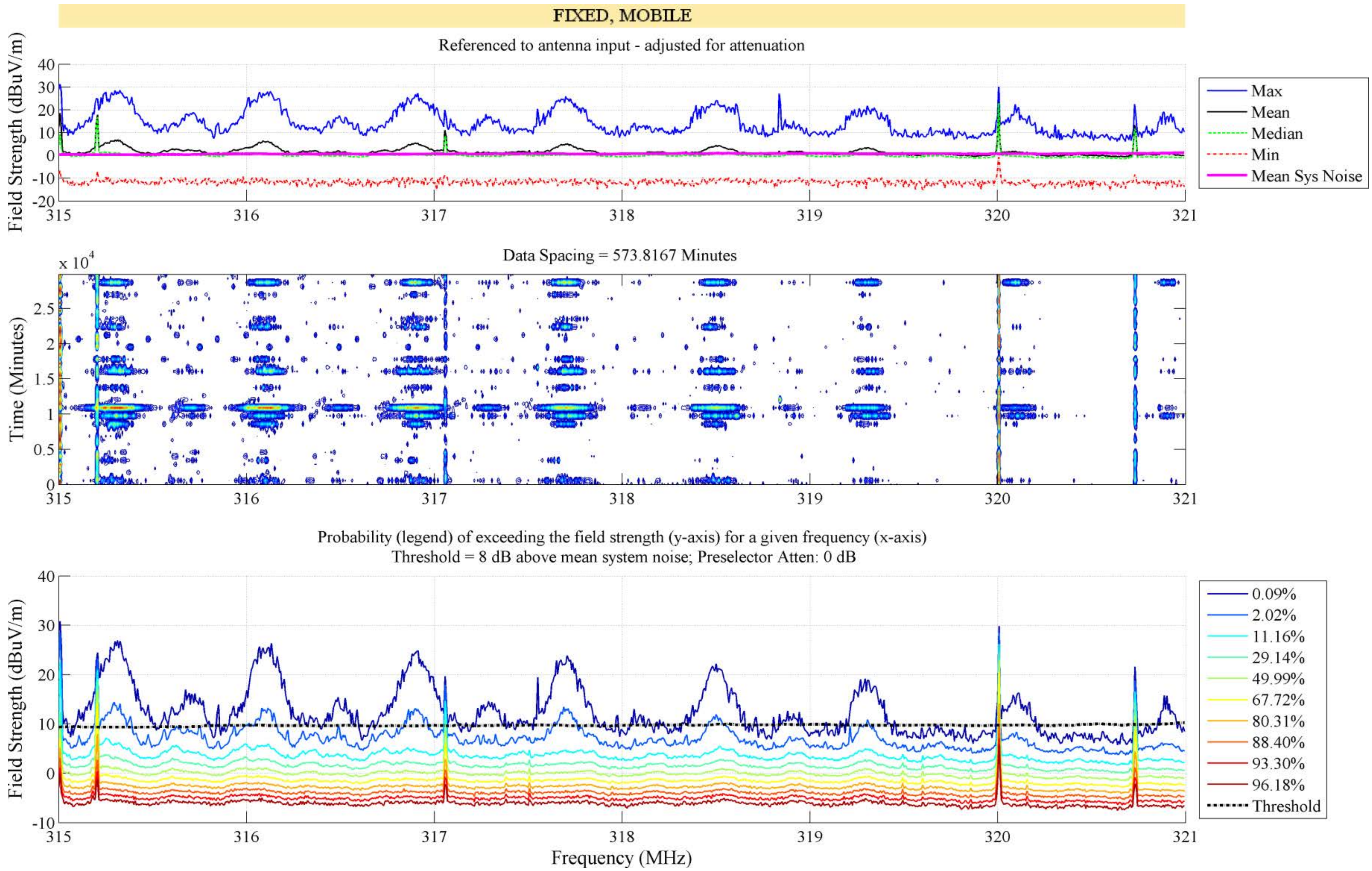

Figure 33. NTIA spectrum survey results from 315 to 321 MHz in Denver, CO, 2011.

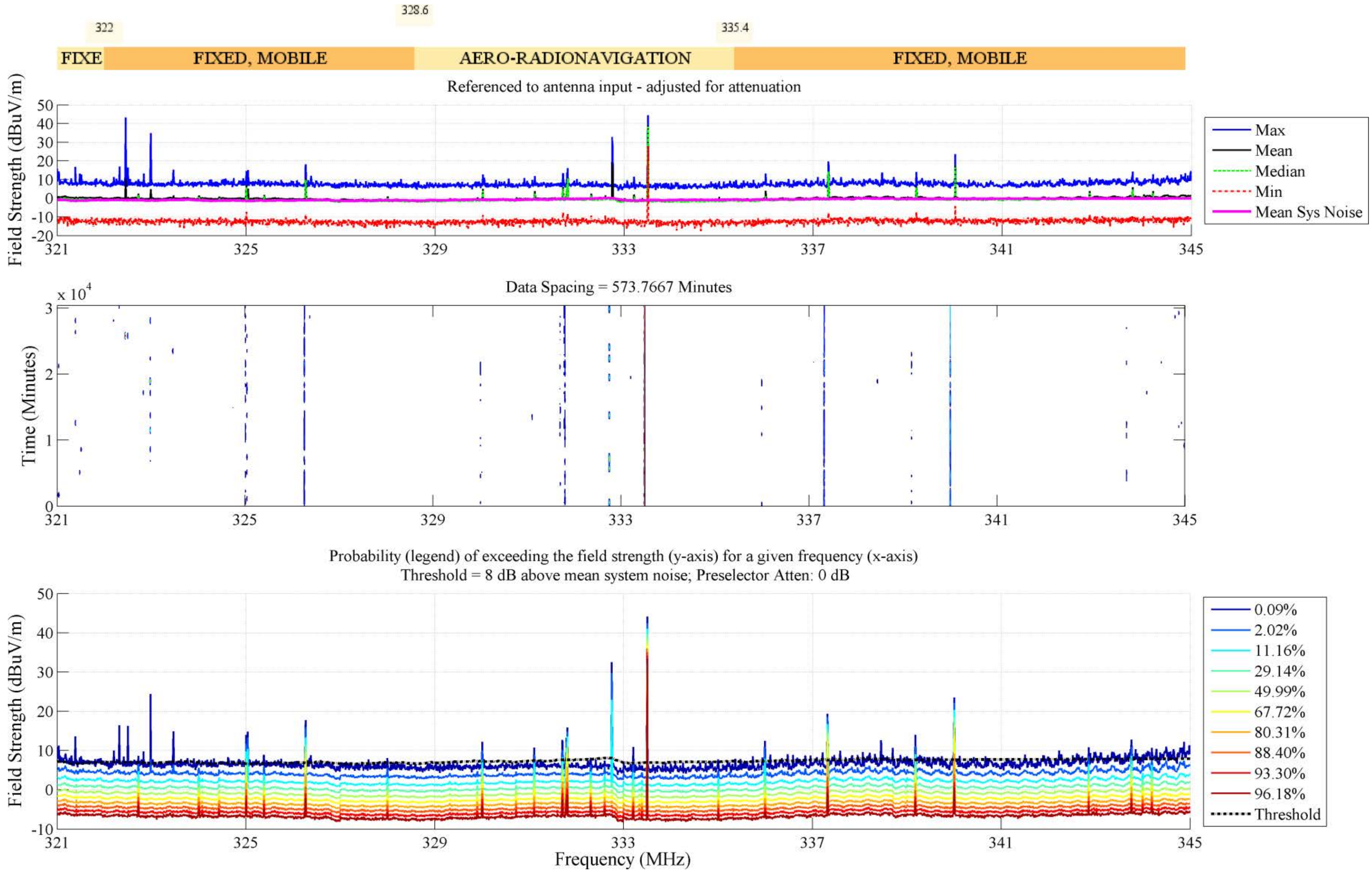

Figure 34. NTIA spectrum survey results from 321 to 345 MHz in Denver, CO, 2011.

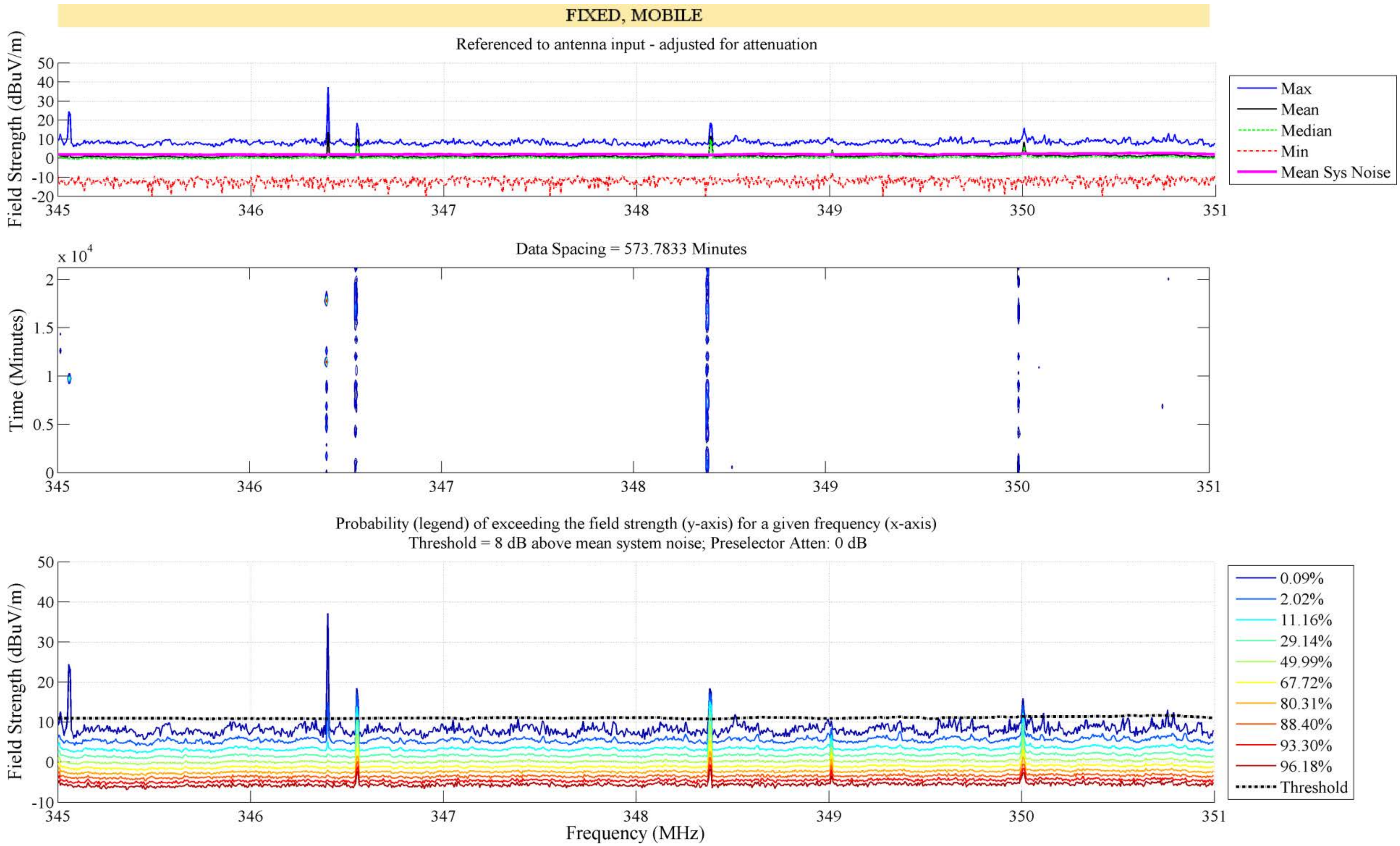

Figure 35. NTIA spectrum survey results from 345 to 351 MHz in Denver, CO, 2011.

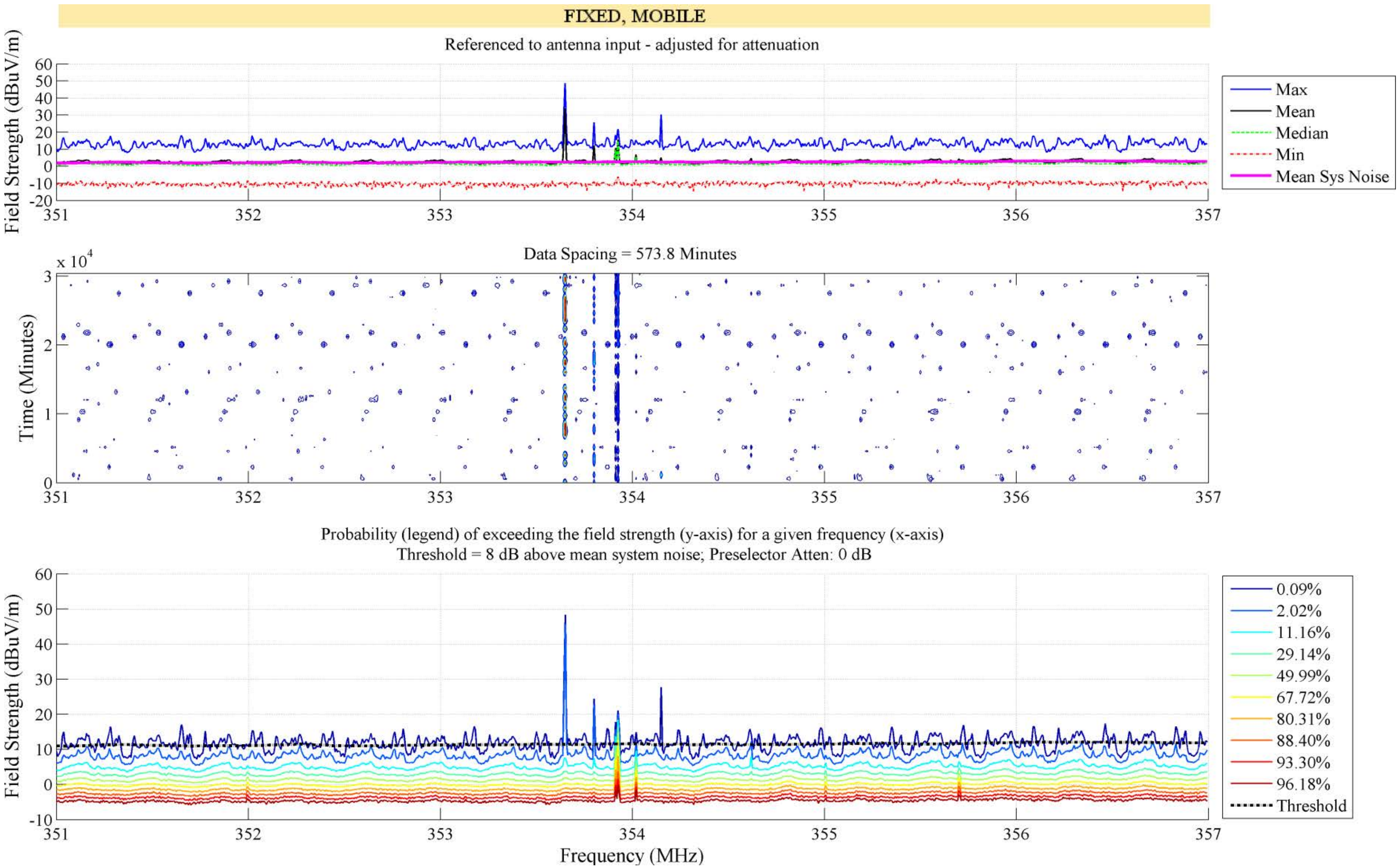

Figure 36. NTIA spectrum survey results from 351 to 357 MHz in Denver, CO, 2011.

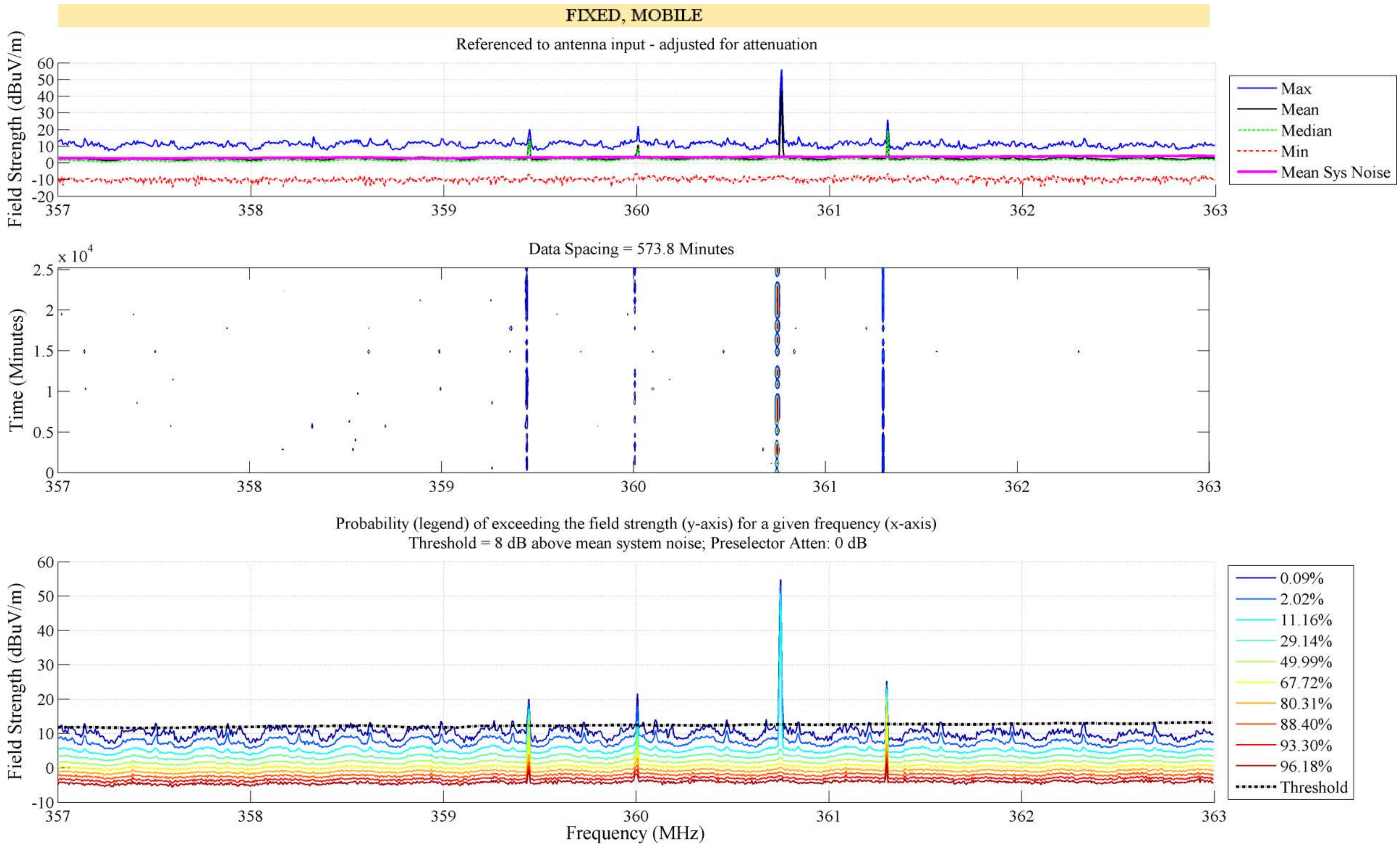

Figure 37. NTIA spectrum survey results from 357 to 363 MHz in Denver, CO, 2011.

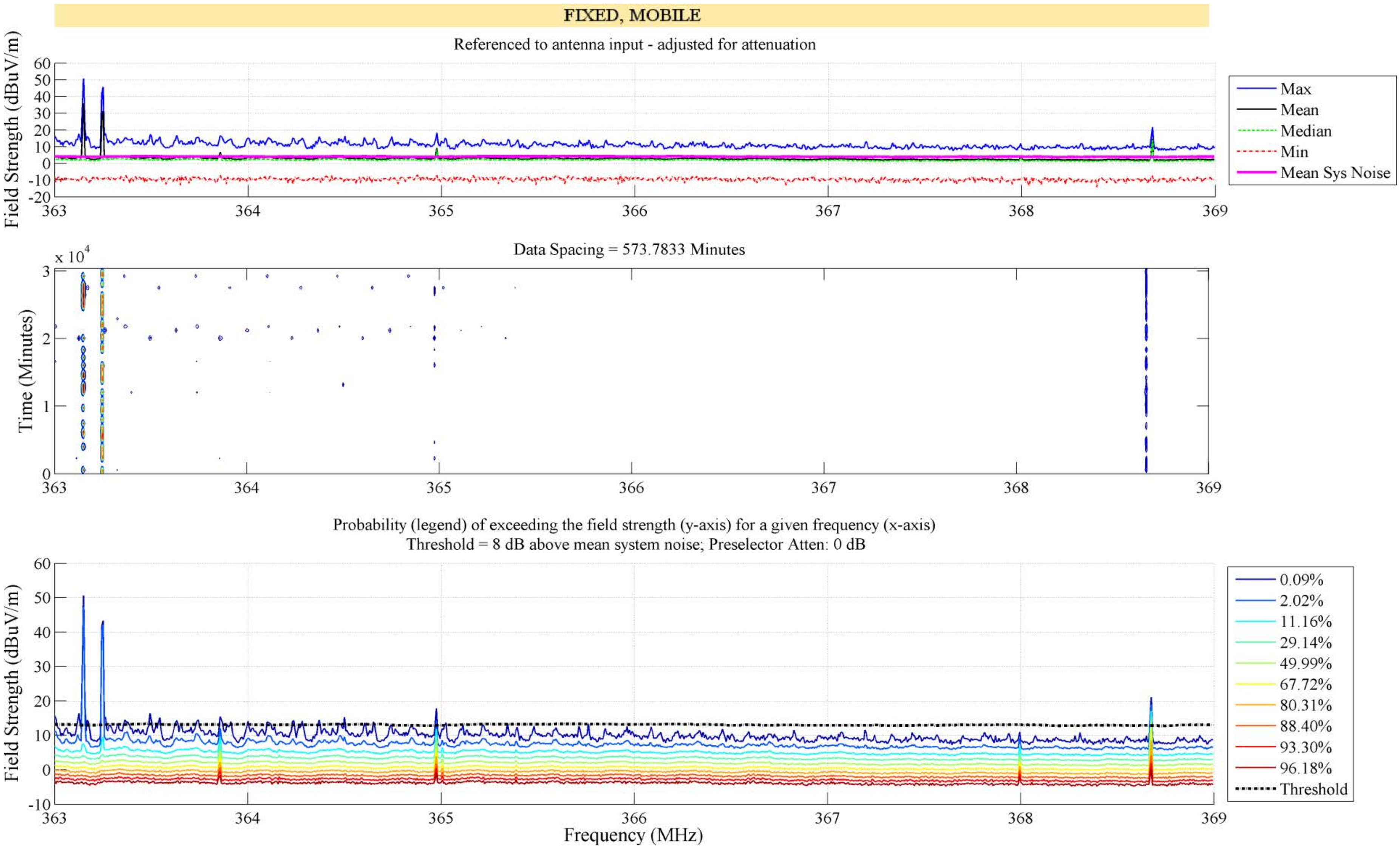

Figure 38. NTIA spectrum survey results from 363 to 369 MHz in Denver, CO, 2011.

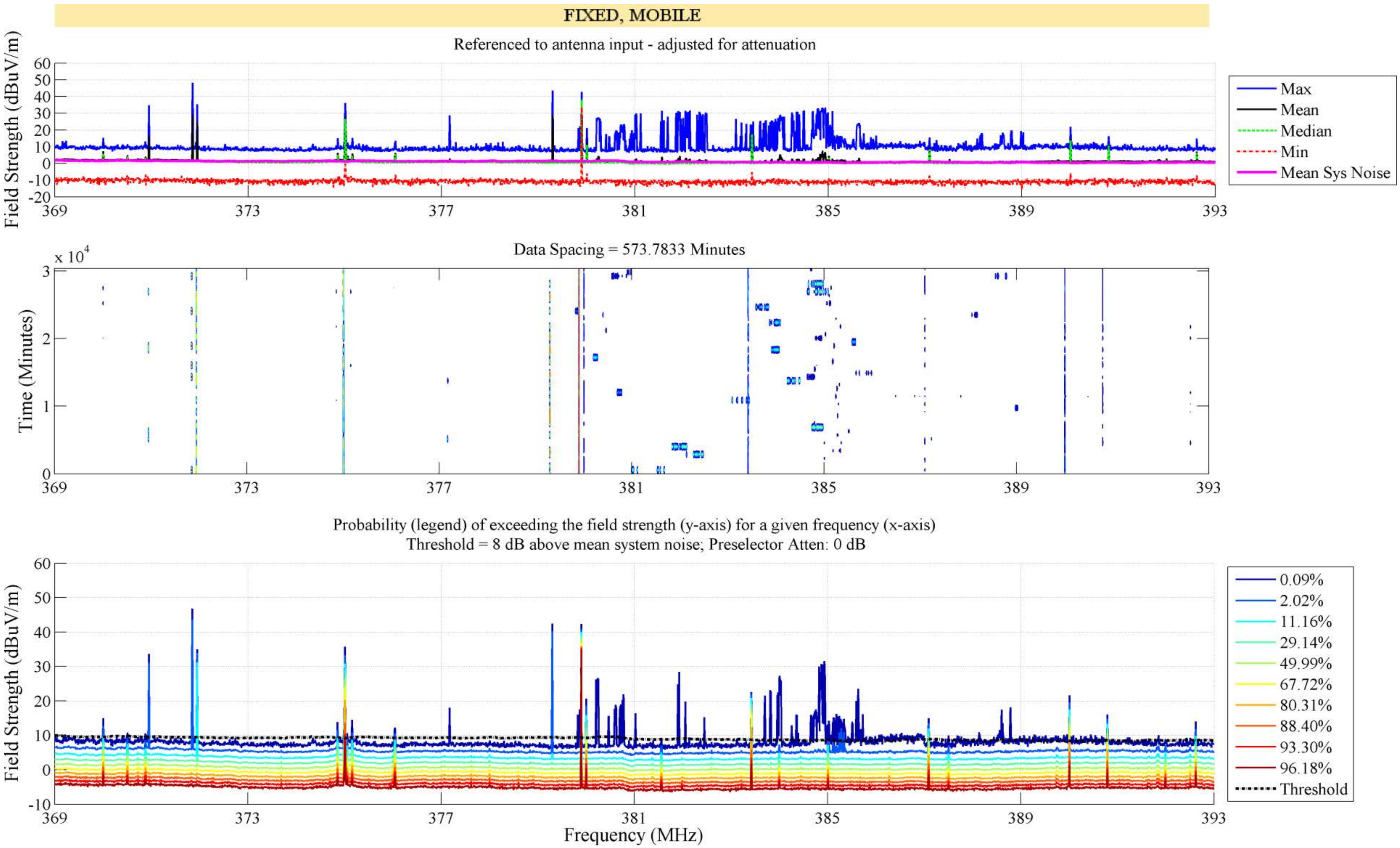

Figure 39. NTIA spectrum survey results from 369 to 393 MHz in Denver, CO, 2011.

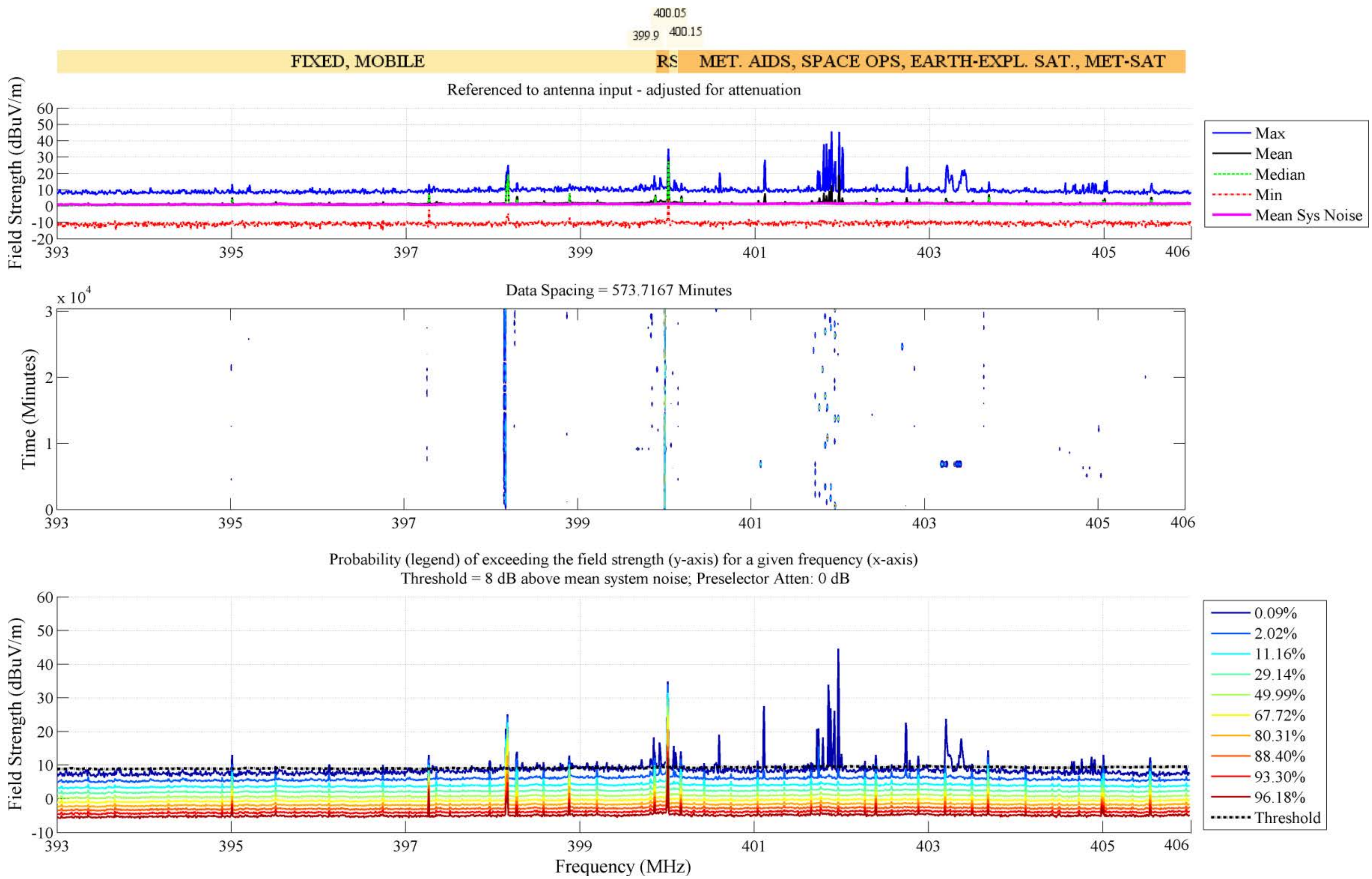

Figure 40. NTIA spectrum survey results from 393 to 406 MHz in Denver, CO, 2011.

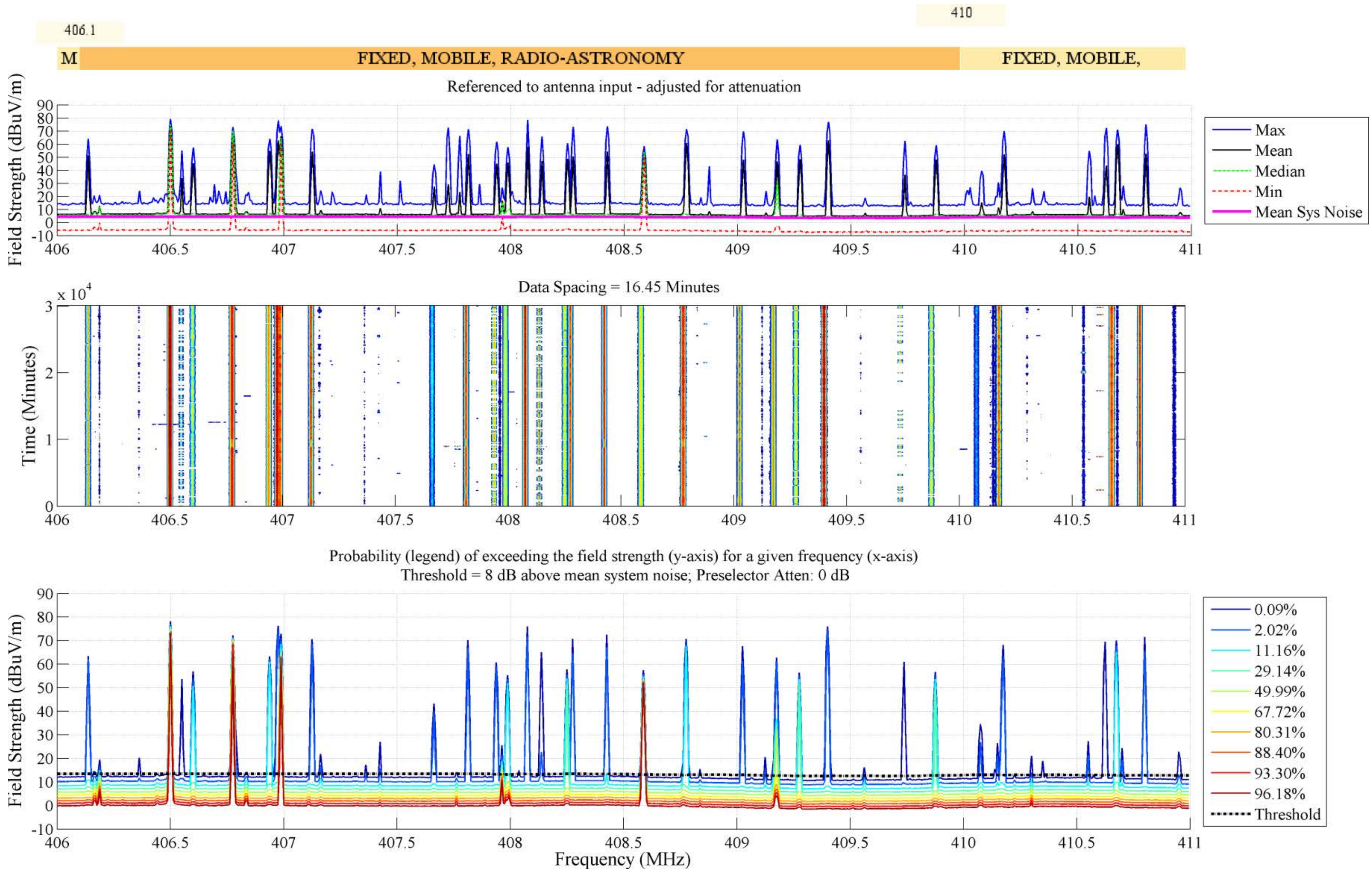

Figure 41. NTIA spectrum survey results from 406 to 411 MHz in Denver, CO, 2011.

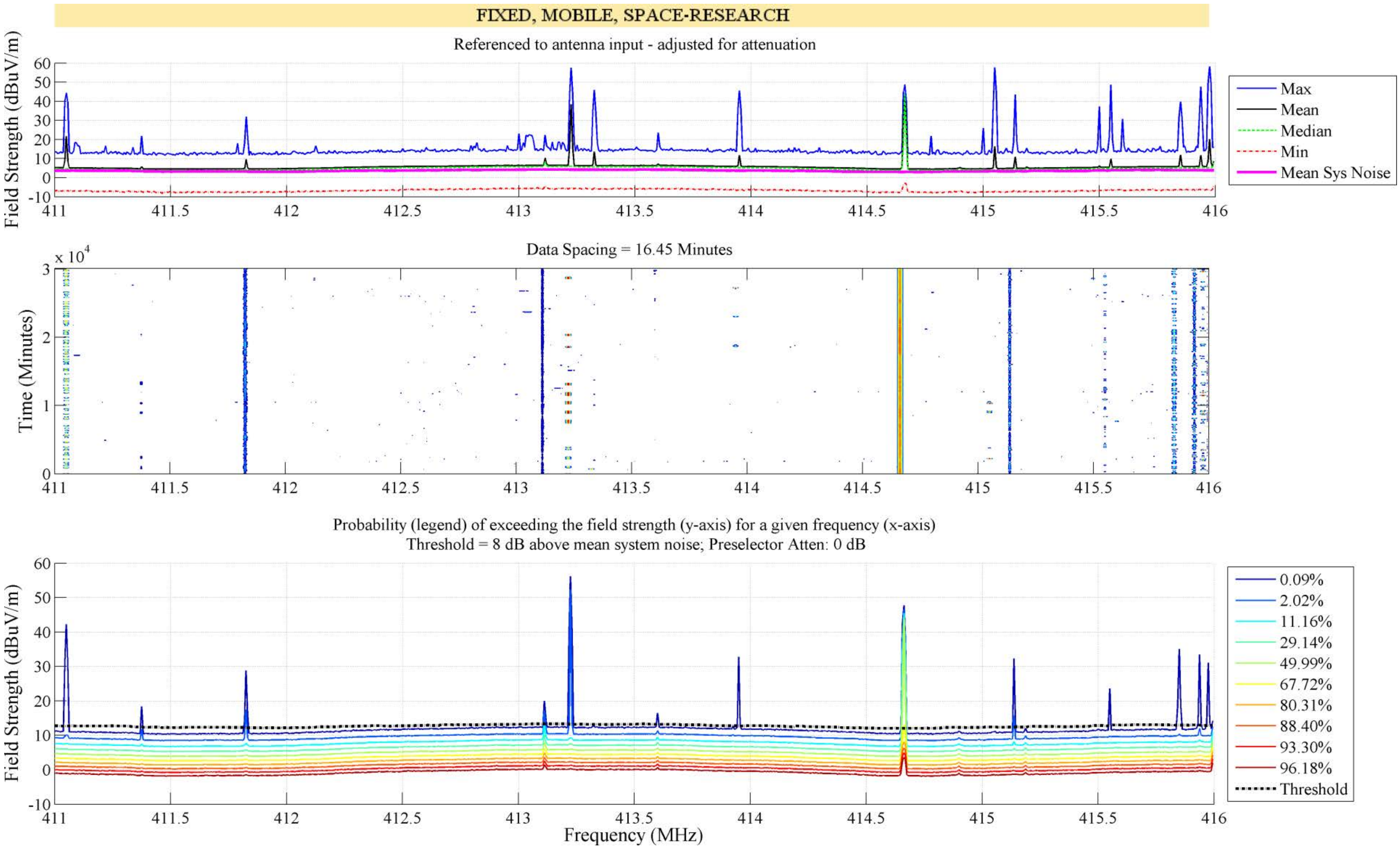

Figure 42. NTIA spectrum survey results from 411 to 416 MHz in Denver, CO, 2011.

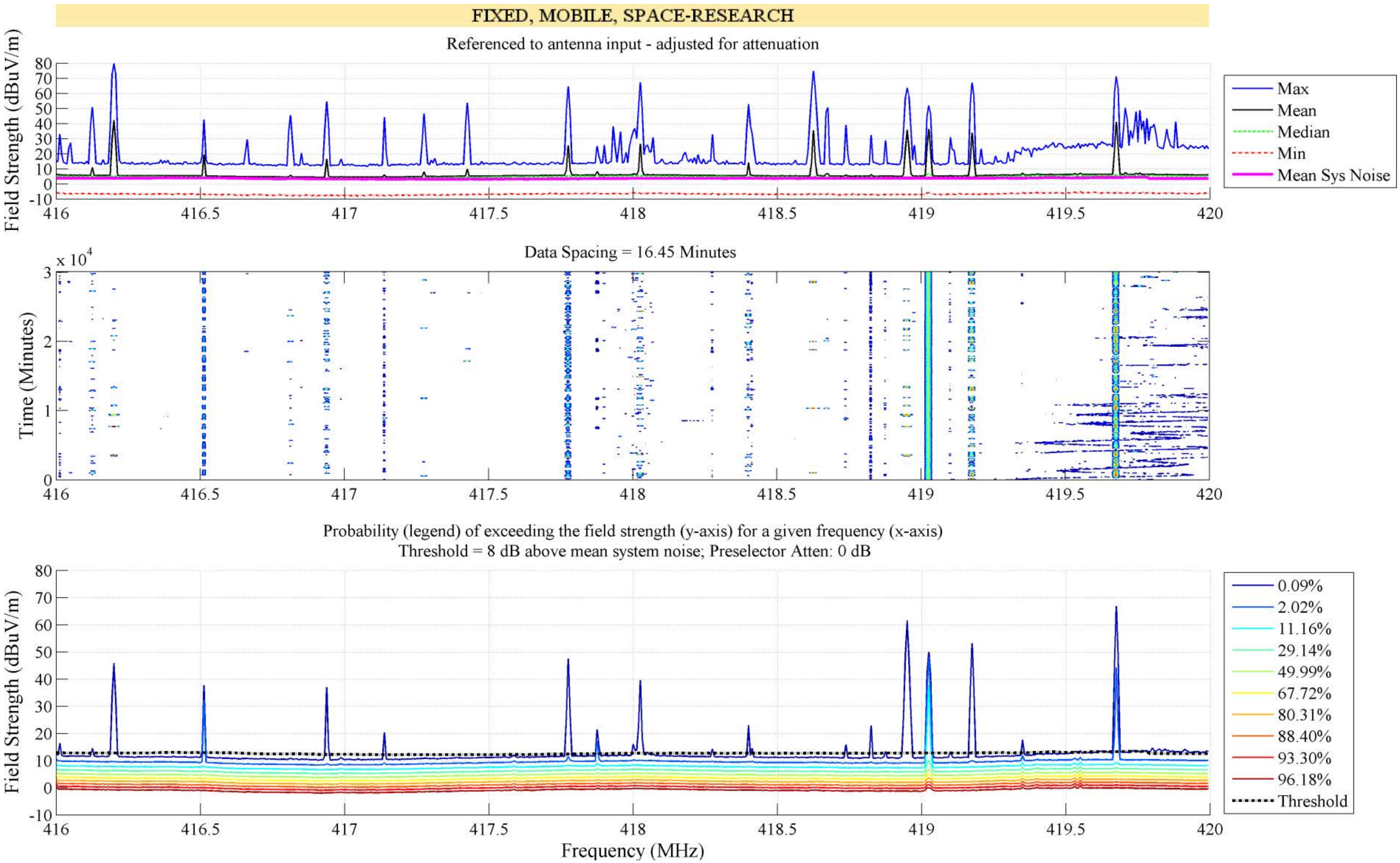

Figure 43. NTIA spectrum survey results from 416 to 420 MHz in Denver, CO, 2011.

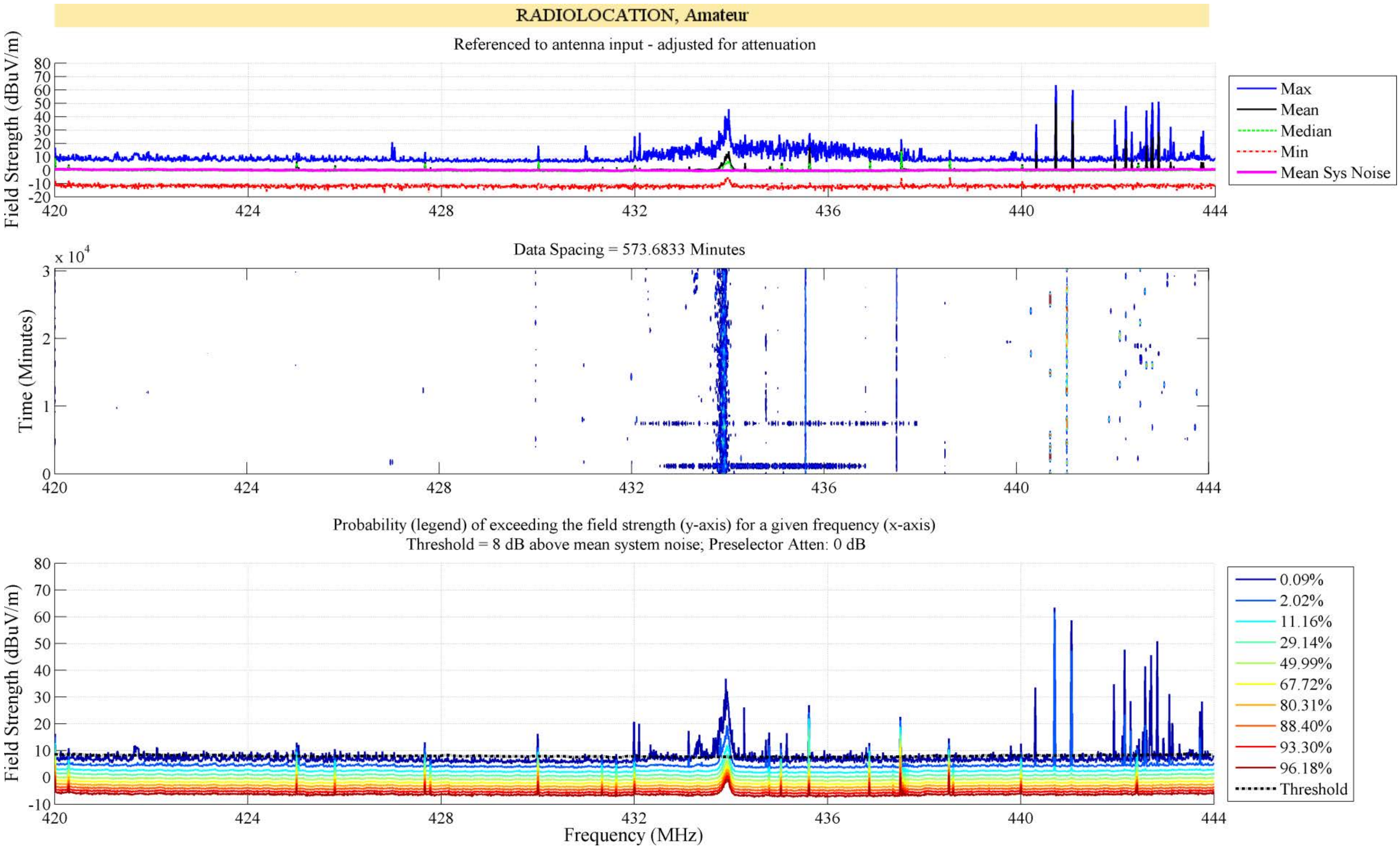

Figure 44. NTIA spectrum survey results from 420 to 444 MHz in Denver, CO, 2011.

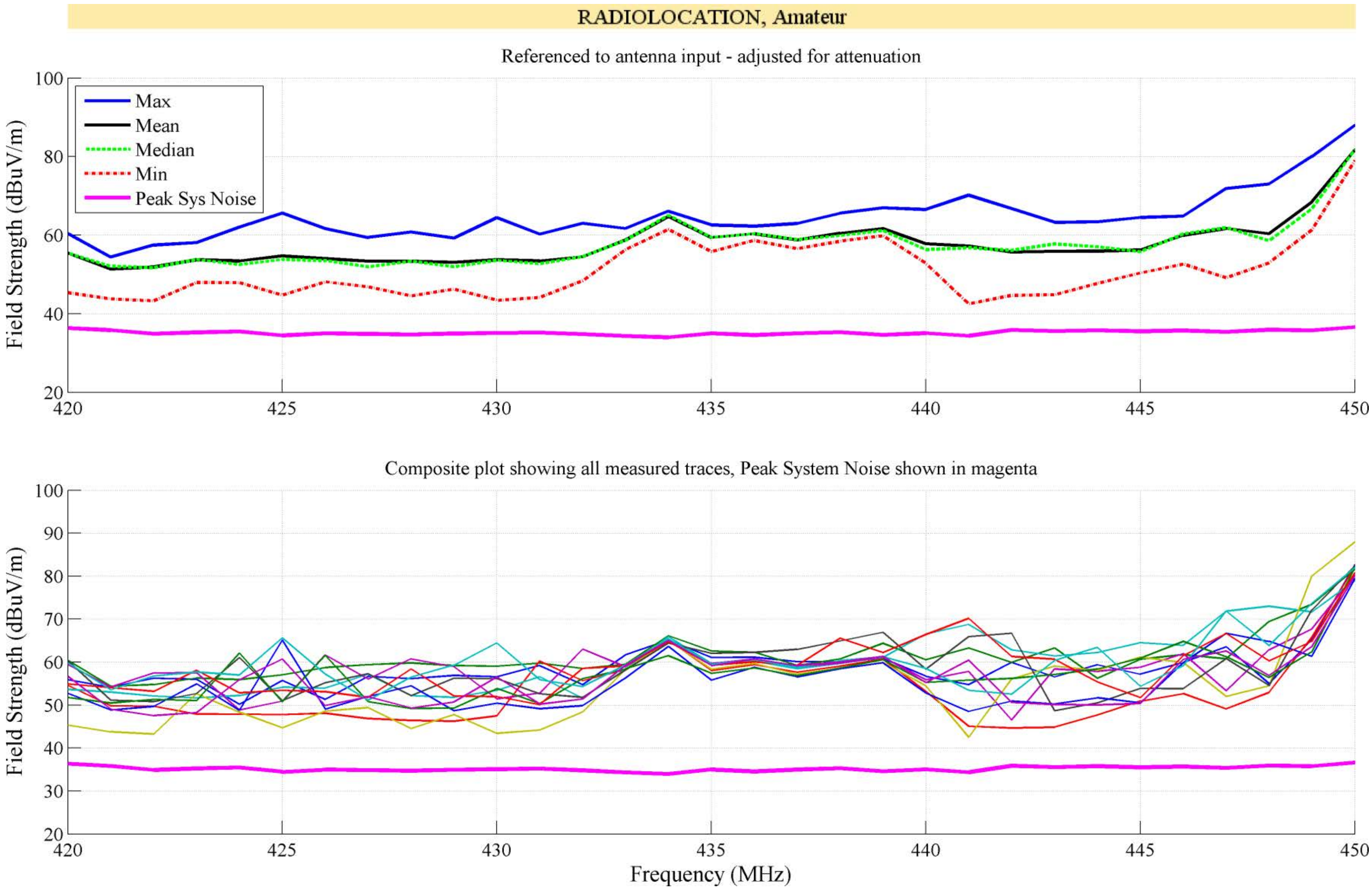

Figure 45. NTIA spectrum survey results from 420 to 450 MHz in Denver, CO, 2011. This measurement was taken using the stepped-spectrum measurement algorithm.

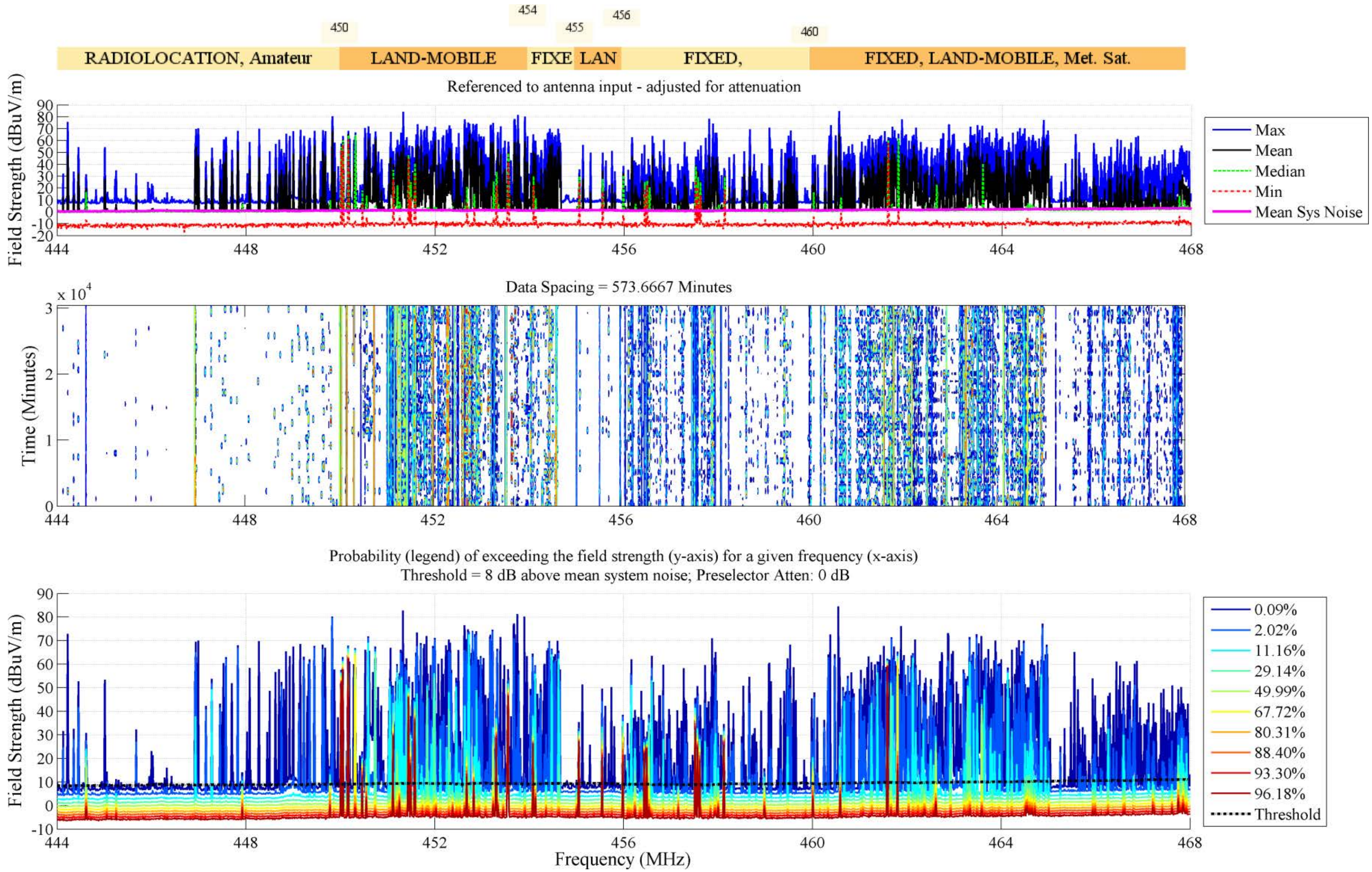

Figure 46. NTIA spectrum survey results from 444 to 468 MHz in Denver, CO, 2011.

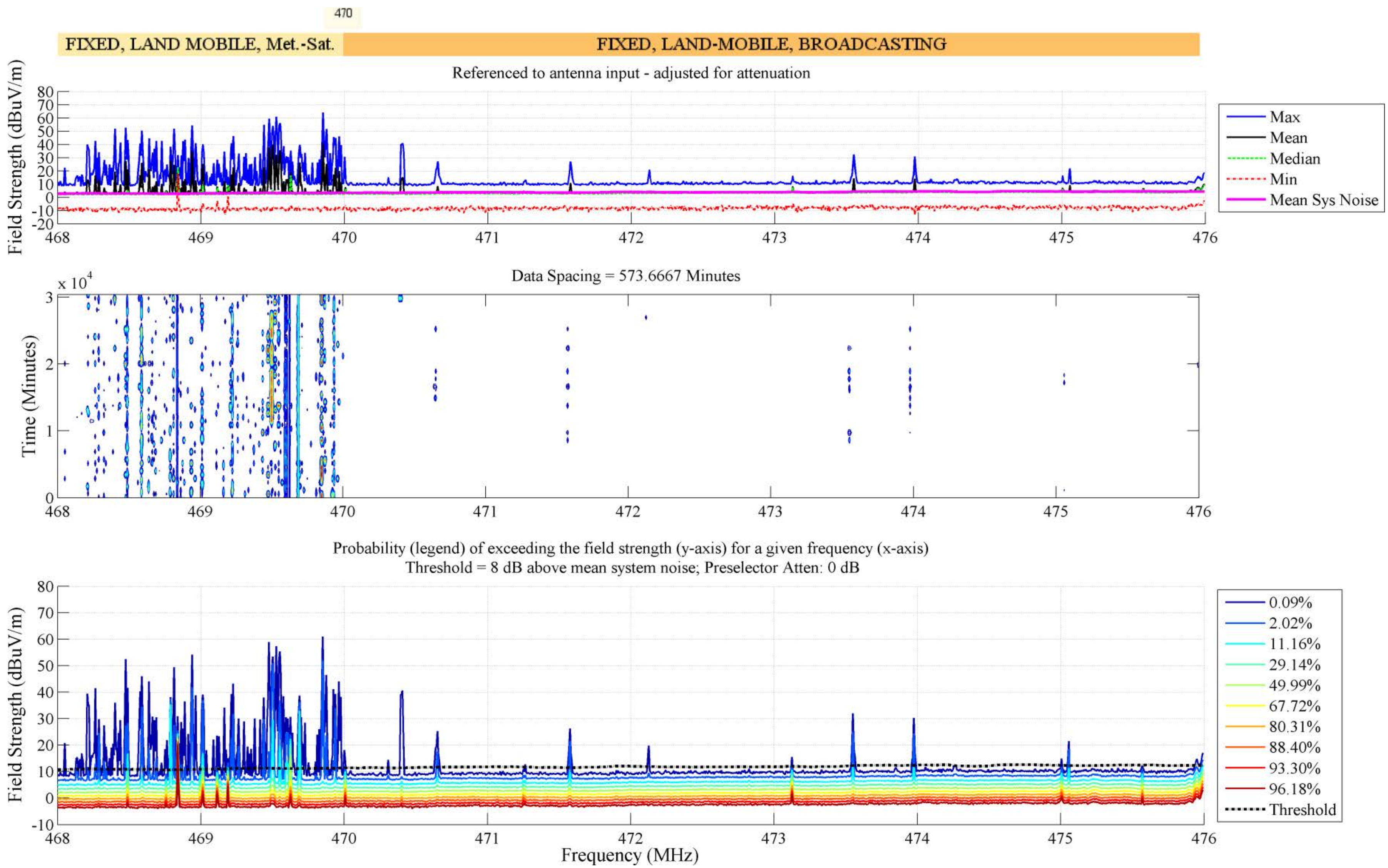

Figure 47. NTIA spectrum survey results from 468 to 476 MHz in Denver, CO, 2011.

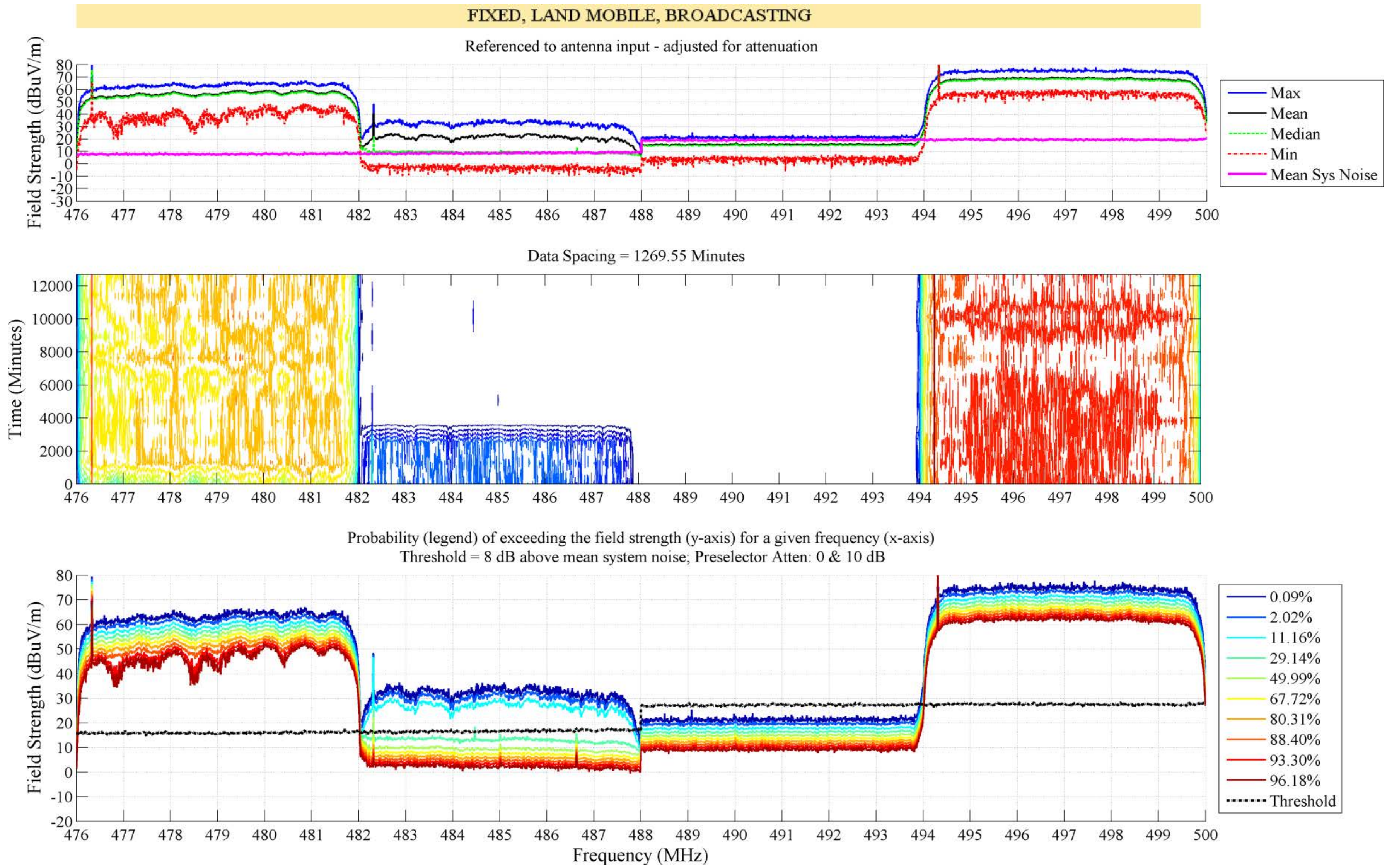

Figure 48. NTIA spectrum survey results from 476 to 500 MHz in Denver, CO, 2011.

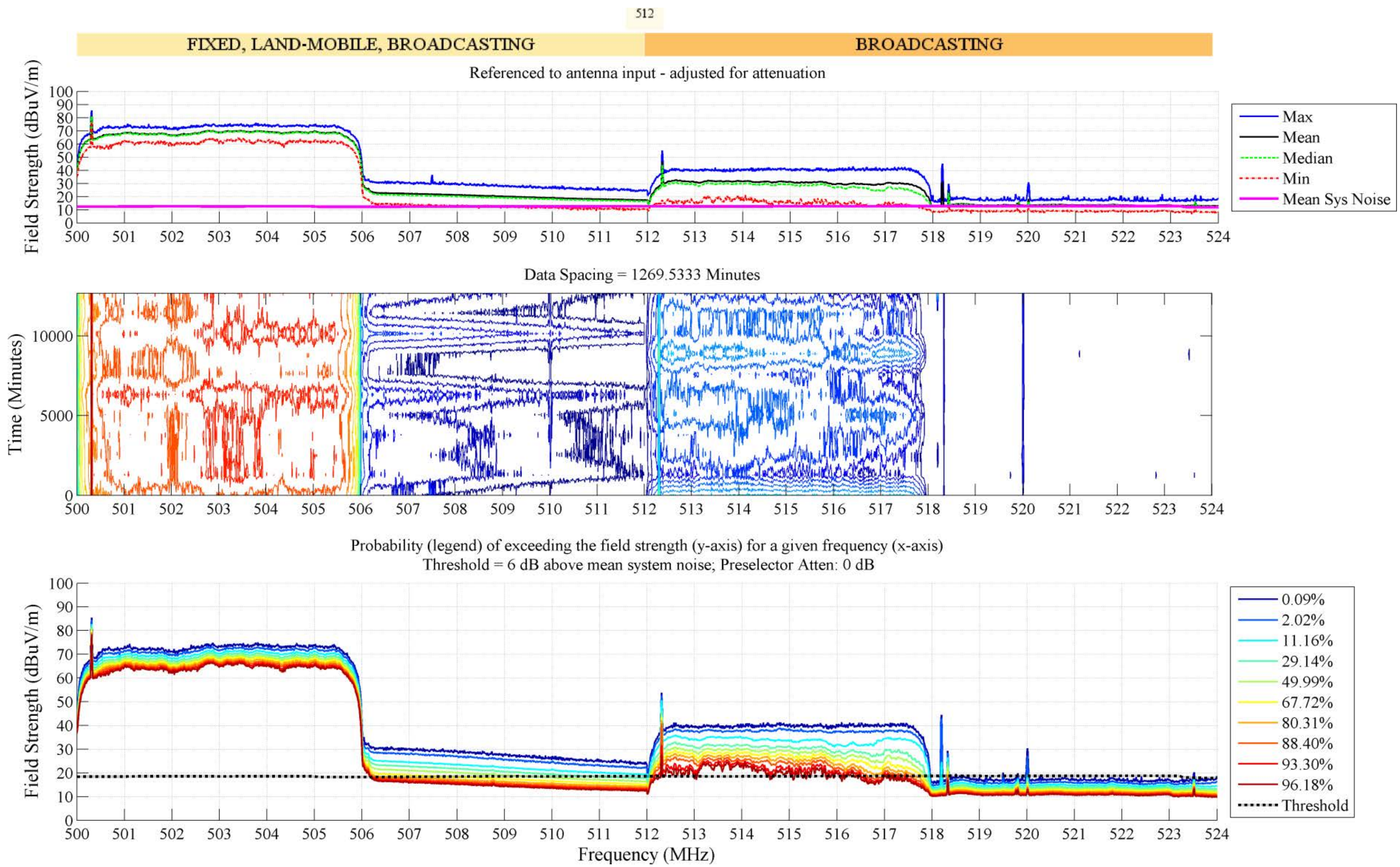

Figure 49. NTIA spectrum survey results from 500 to 524 MHz in Denver, CO, 2011.

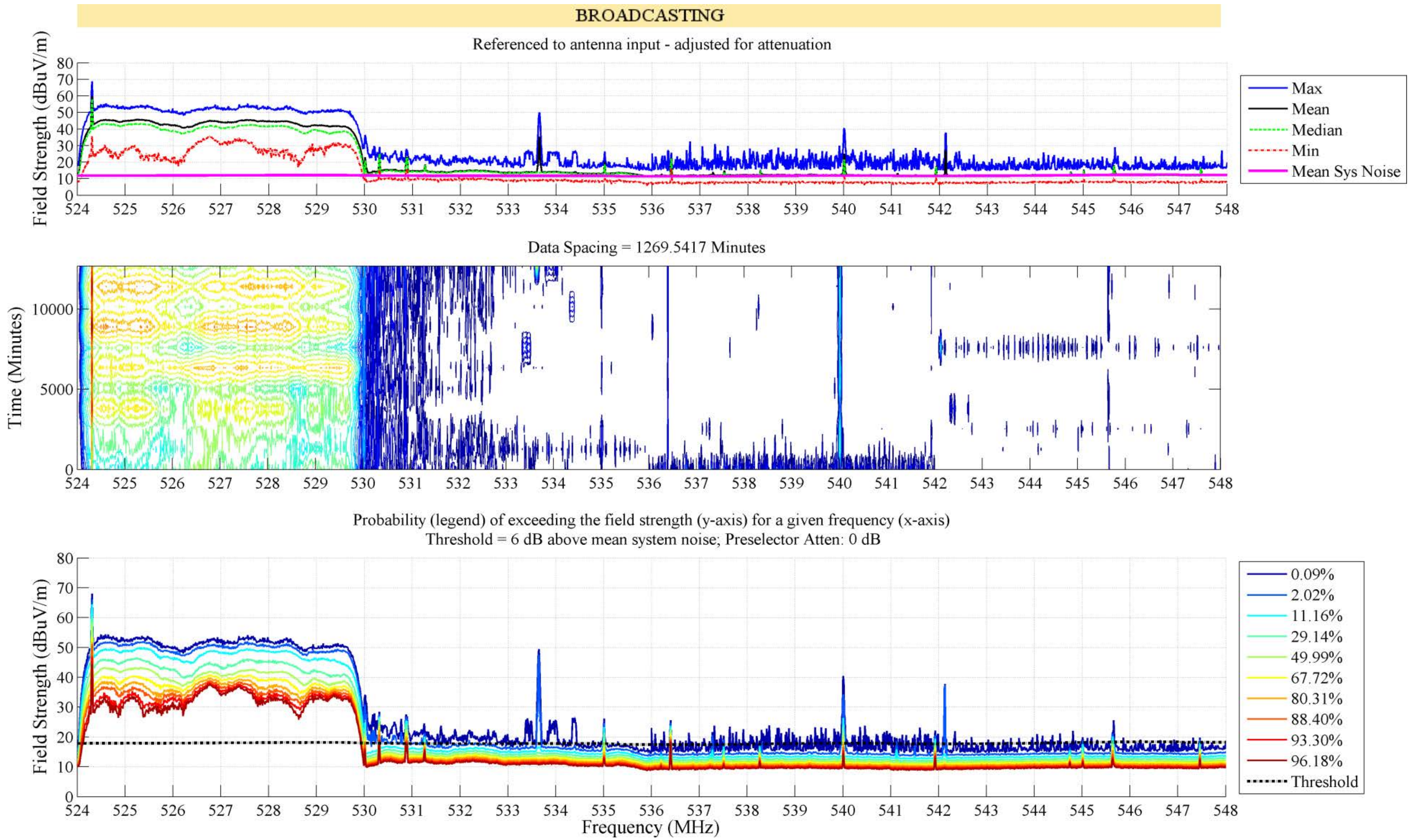

Figure 50. NTIA spectrum survey results from 524 to 548 MHz in Denver, CO, 2011.

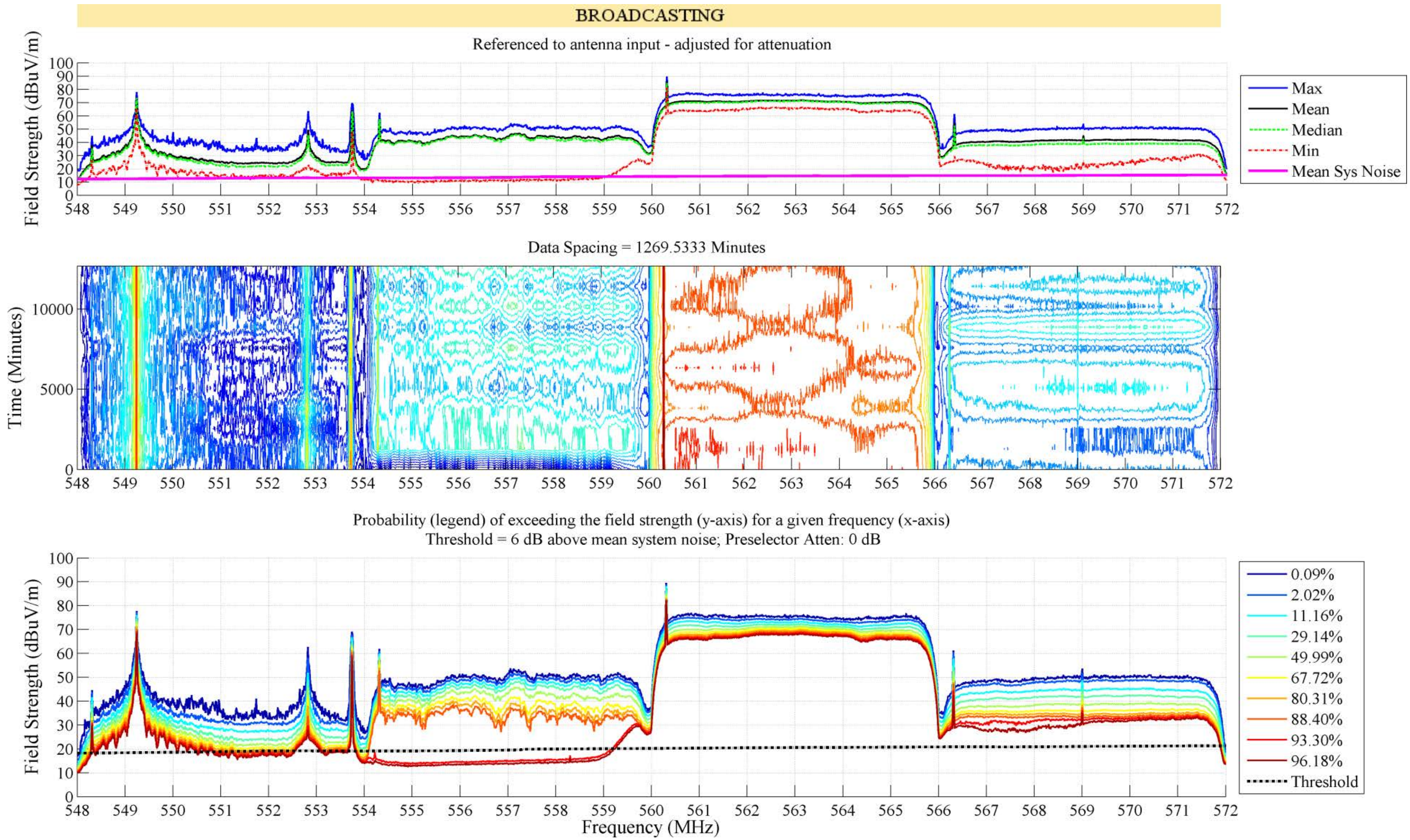

Figure 51. NTIA spectrum survey results from 548 to 572 MHz in Denver, CO, 2011.

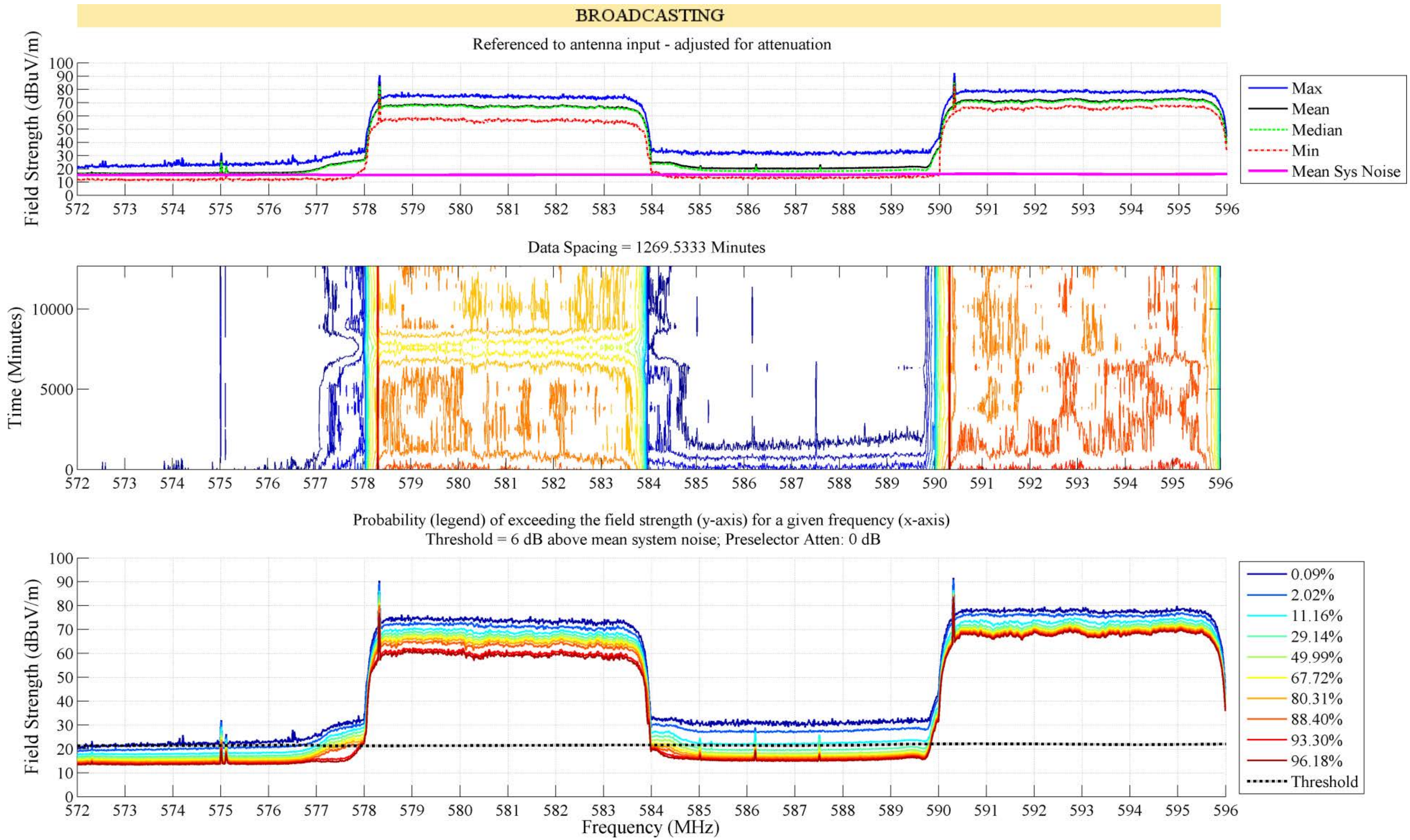

Figure 52. NTIA spectrum survey results from 572 to 596 MHz in Denver, CO, 2011.

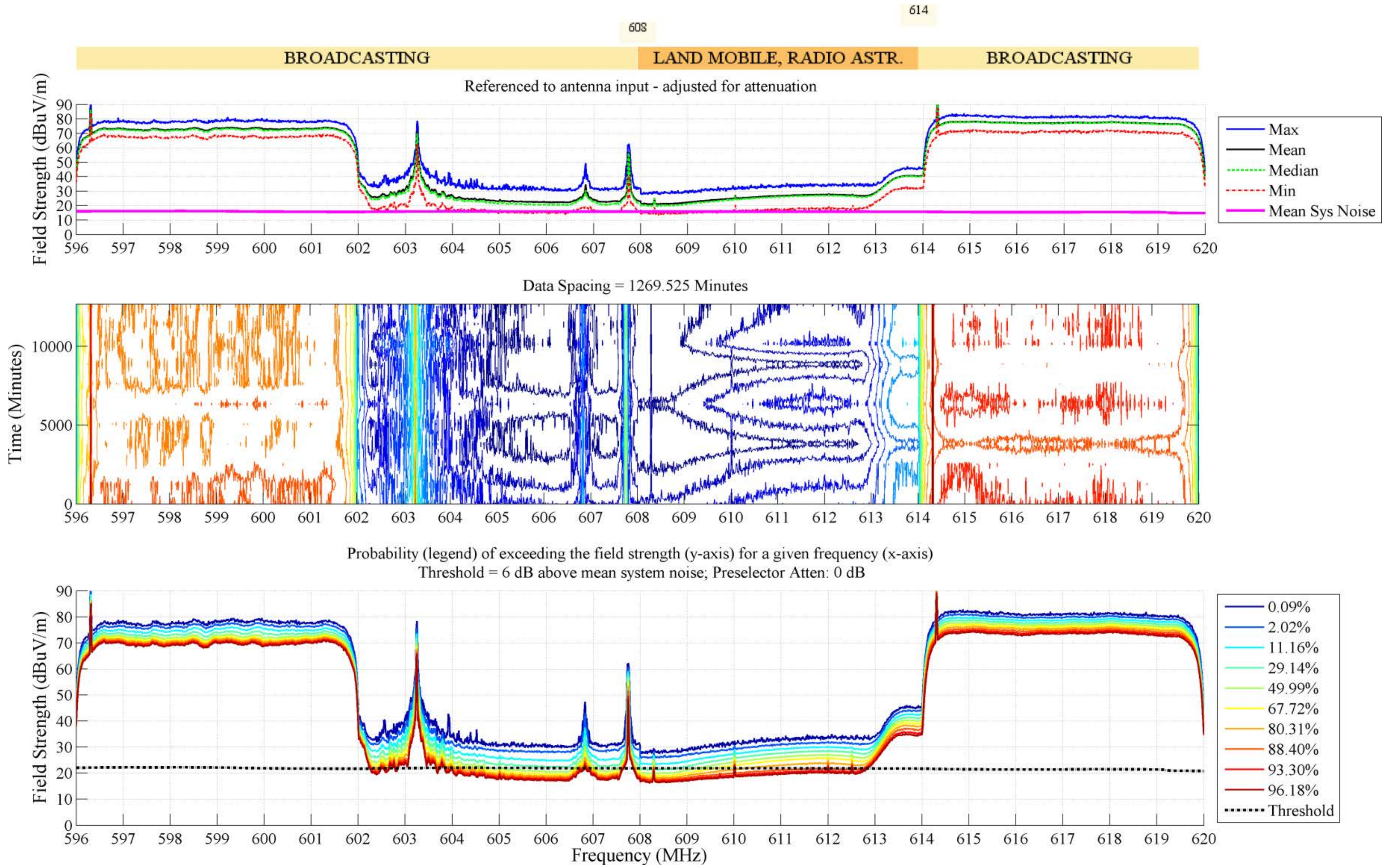

Figure 53. NTIA spectrum survey results from 596 to 620 MHz in Denver, CO, 2011.

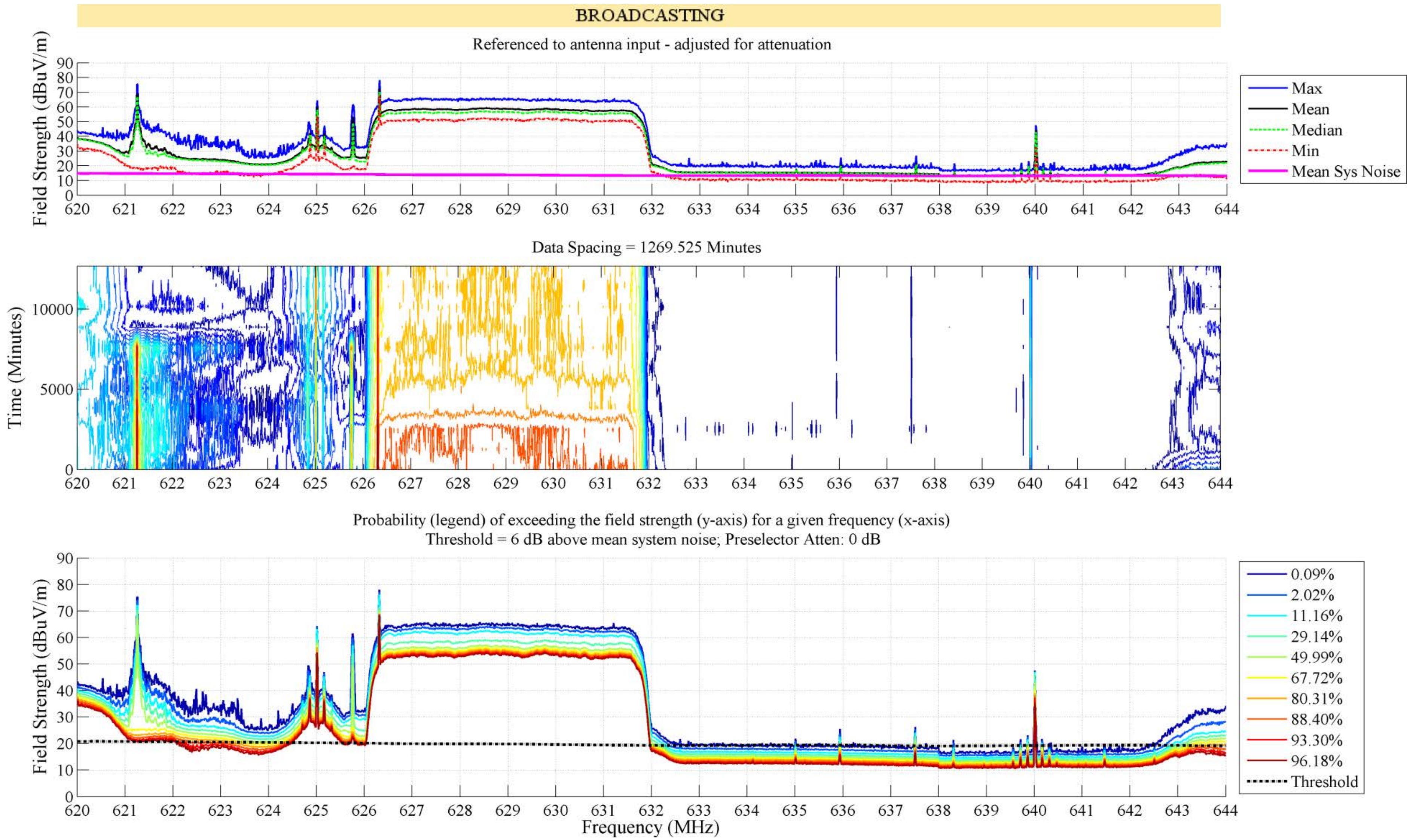

Figure 54. NTIA spectrum survey results from 620 to 644 MHz in Denver, CO, 2011.

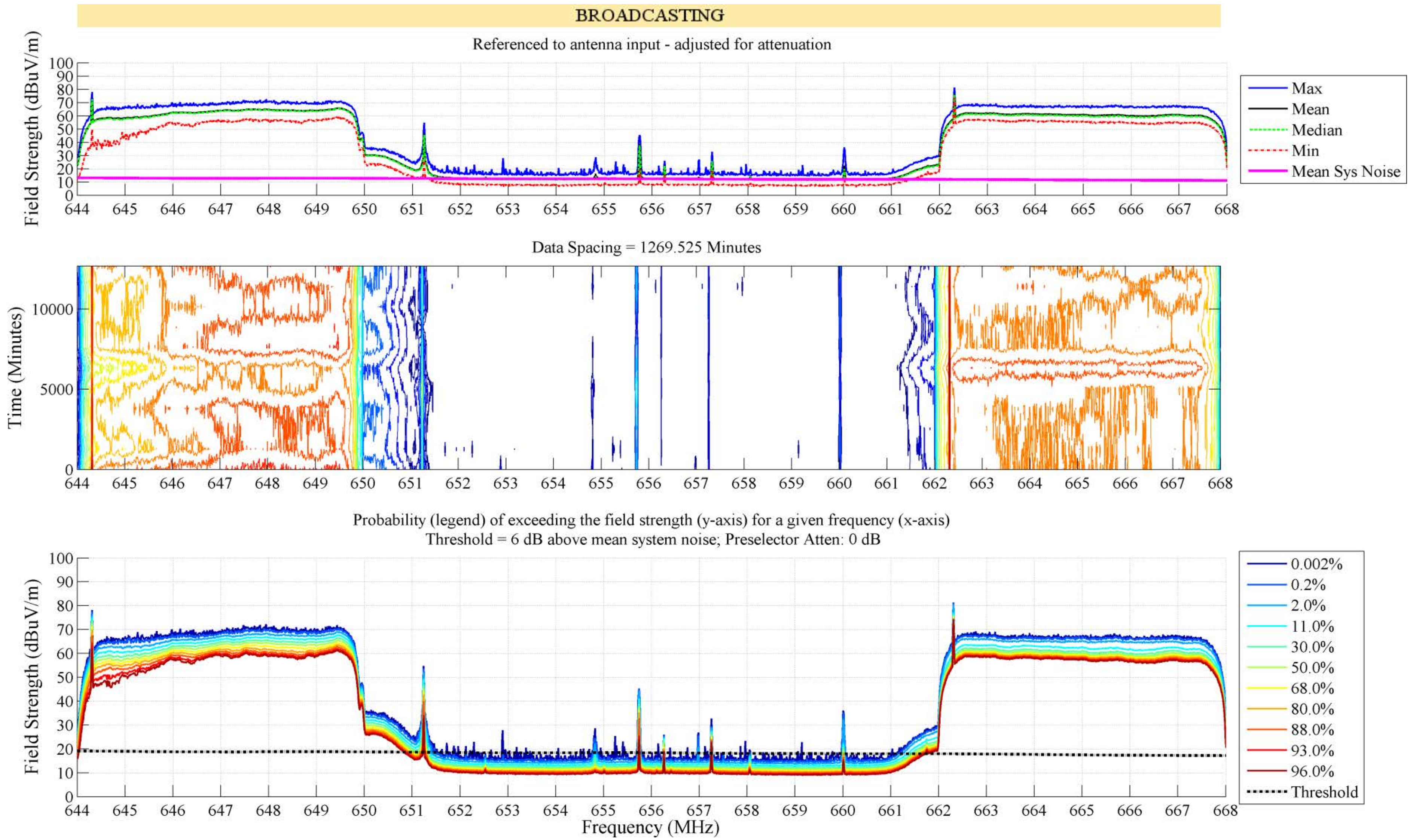

Figure 55. NTIA spectrum survey results from 644 to 668 MHz in Denver, CO, 2011.

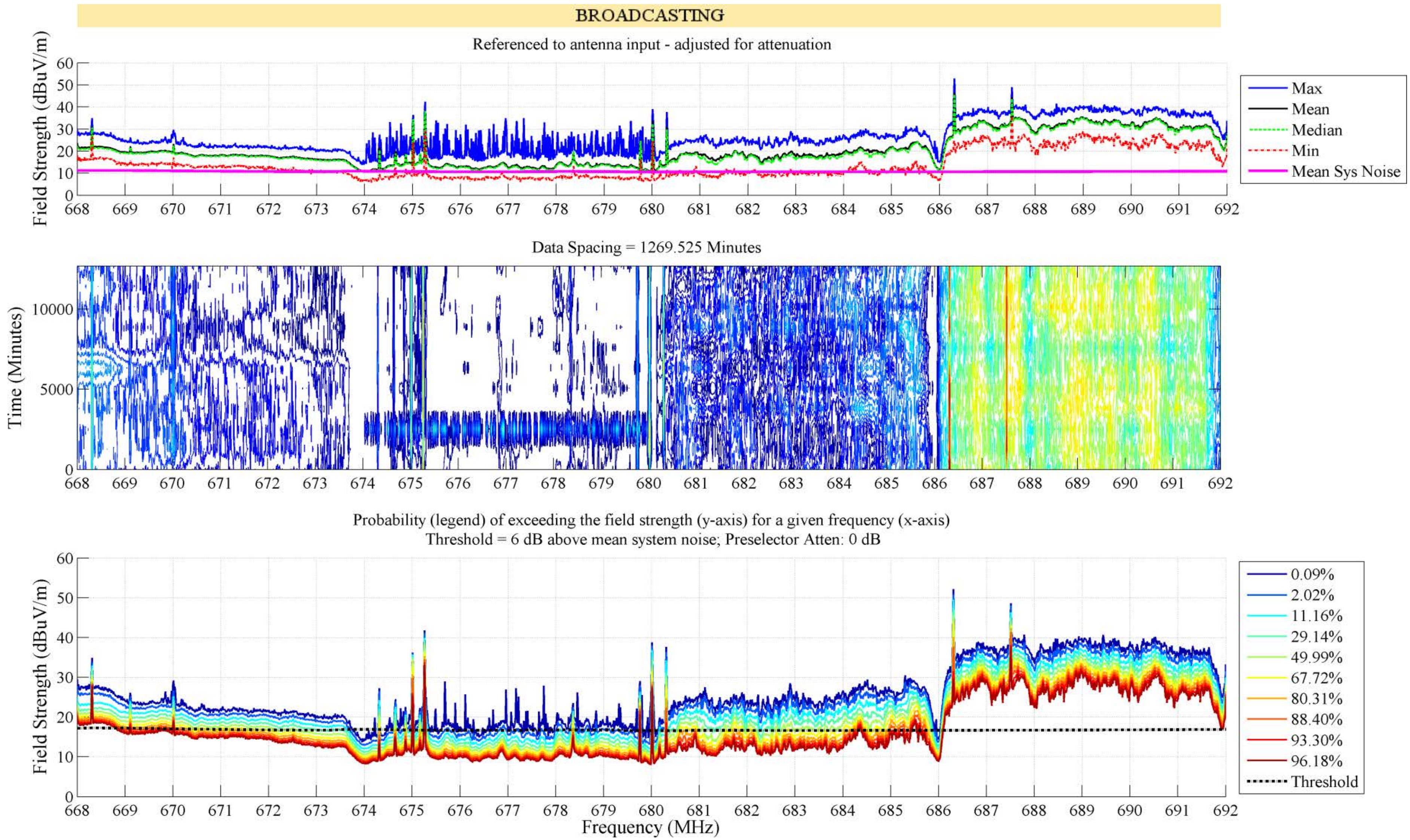

Figure 56. NTIA spectrum survey results from 668 to 692 MHz in Denver, CO, 2011.

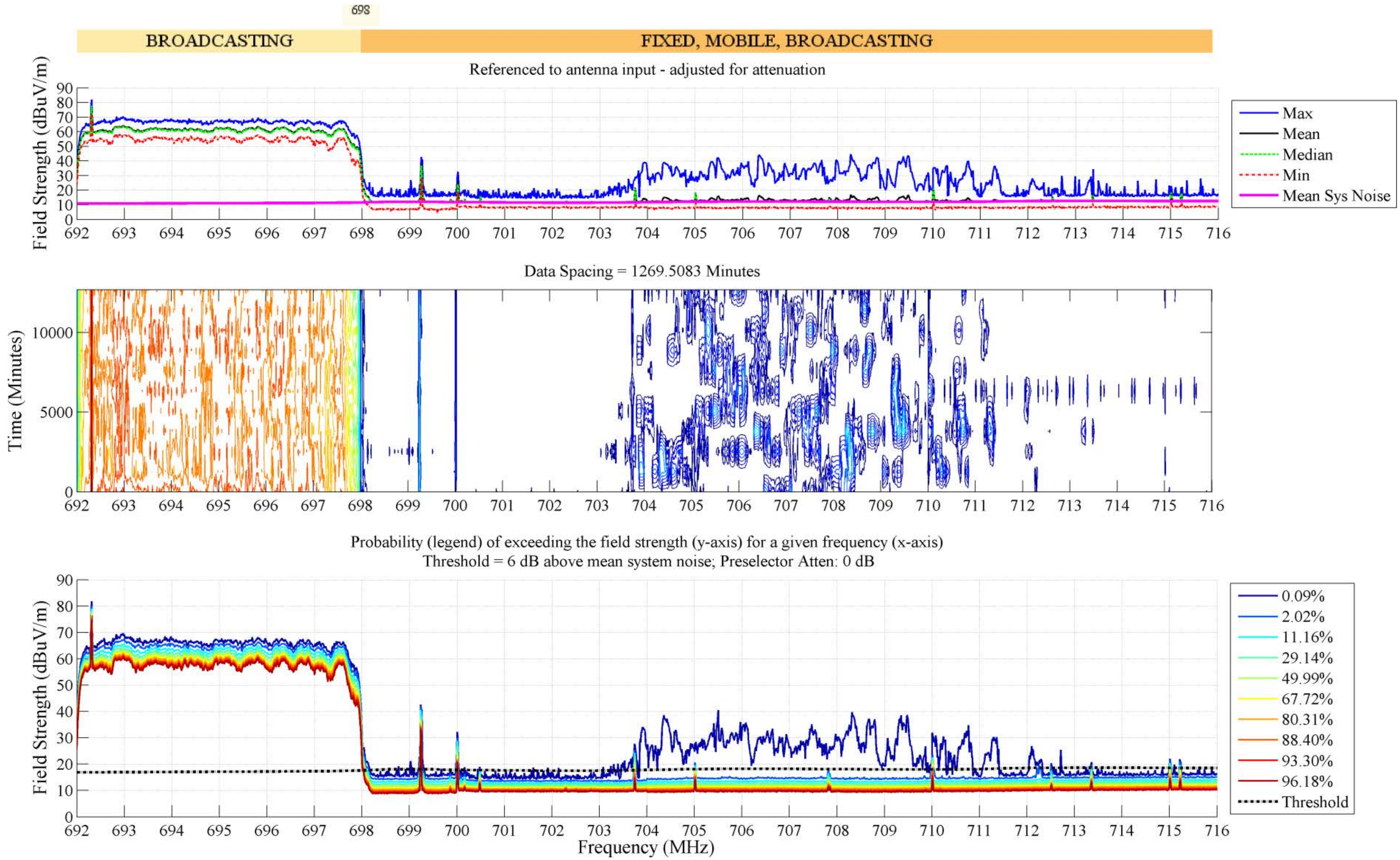

Figure 57. NTIA spectrum survey results from 692 to 716 MHz in Denver, CO, 2011.

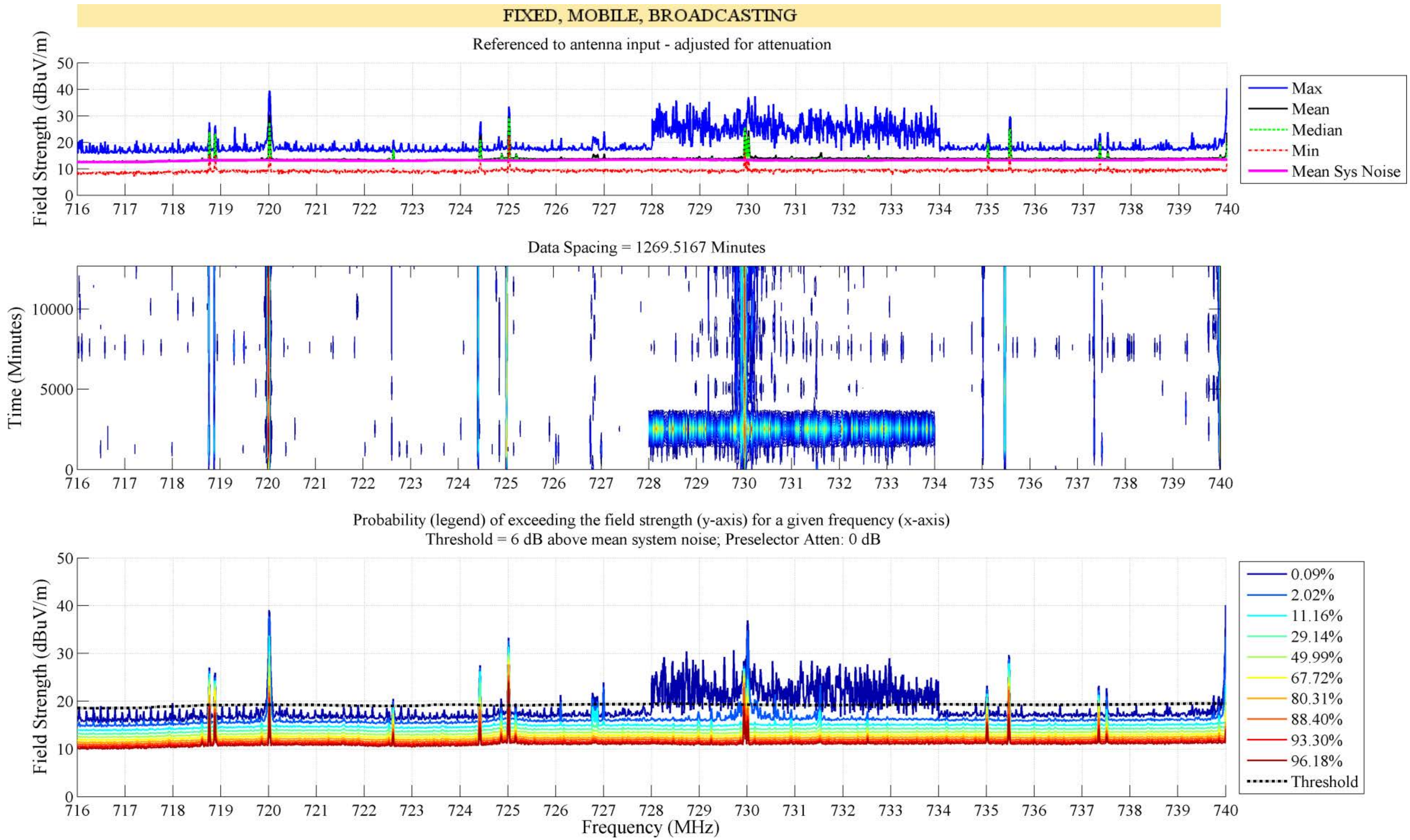

Figure 58. NTIA spectrum survey results from 716 to 740 MHz in Denver, CO, 2011.

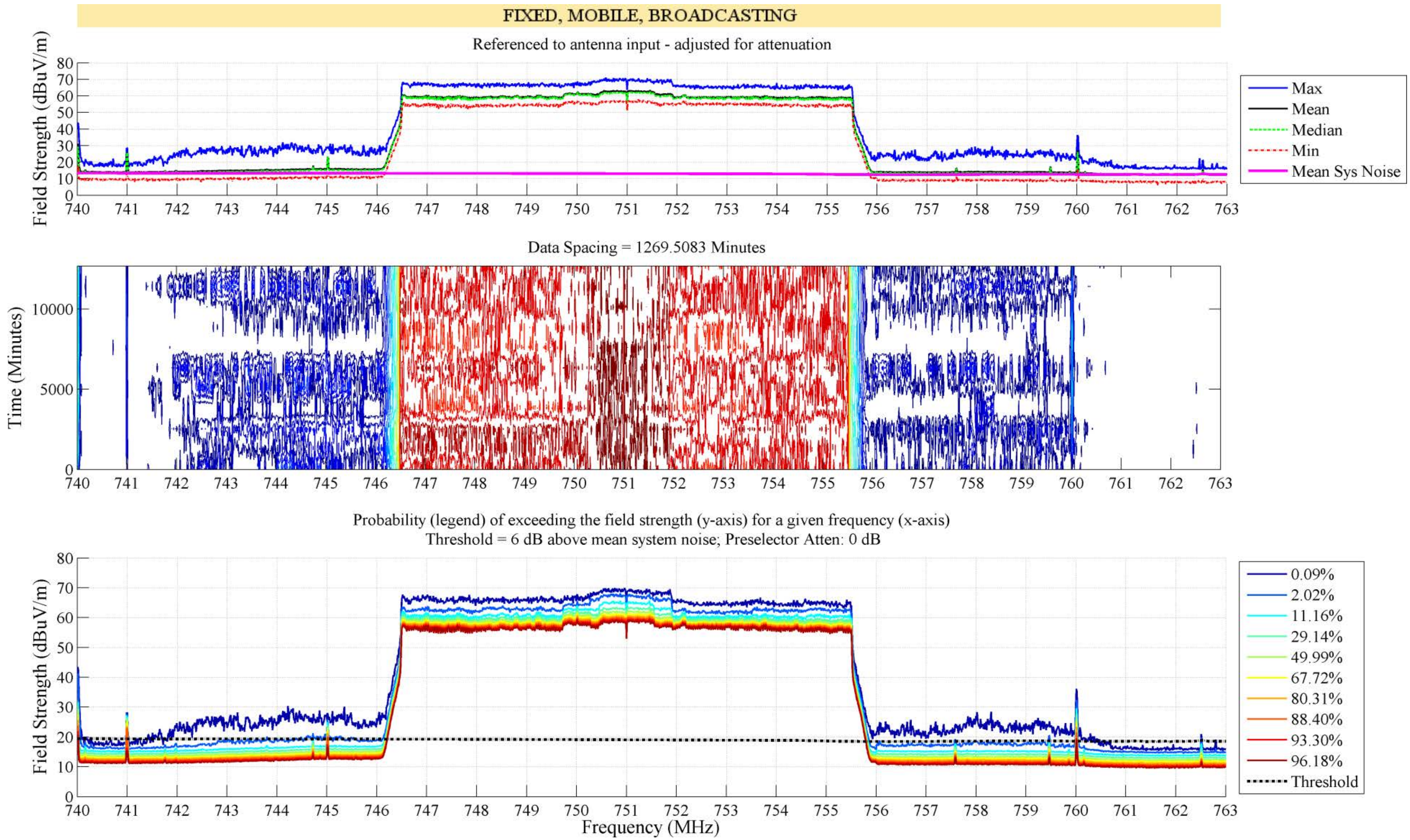

Figure 59. NTIA spectrum survey results from 740 to 763 MHz in Denver, CO, 2011.

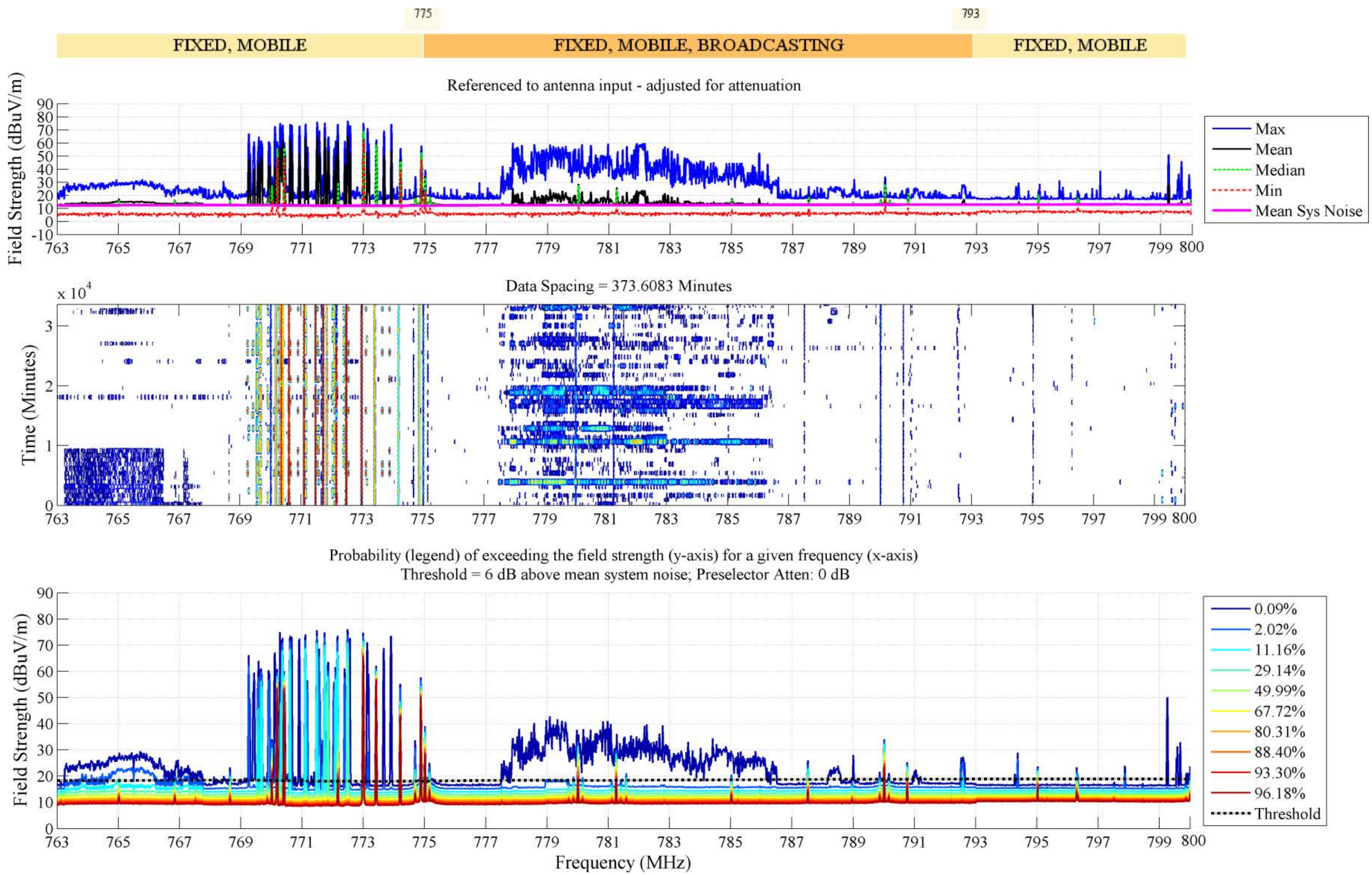

Figure 60. NTIA spectrum survey results from 763 to 800 MHz in Denver, CO, 2011.

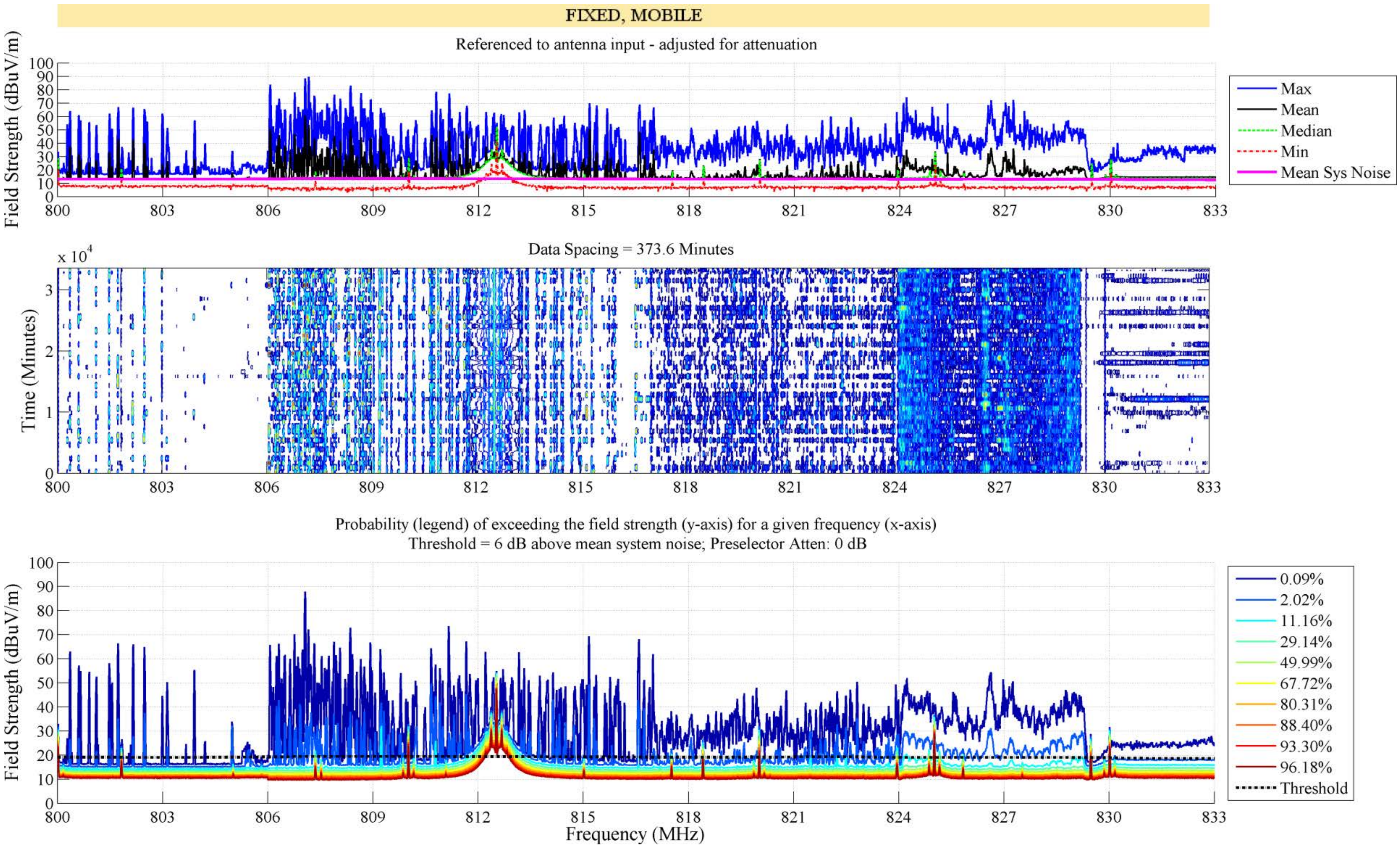

Figure 61. NTIA spectrum survey results from 800 to 833 MHz in Denver, CO, 2011.

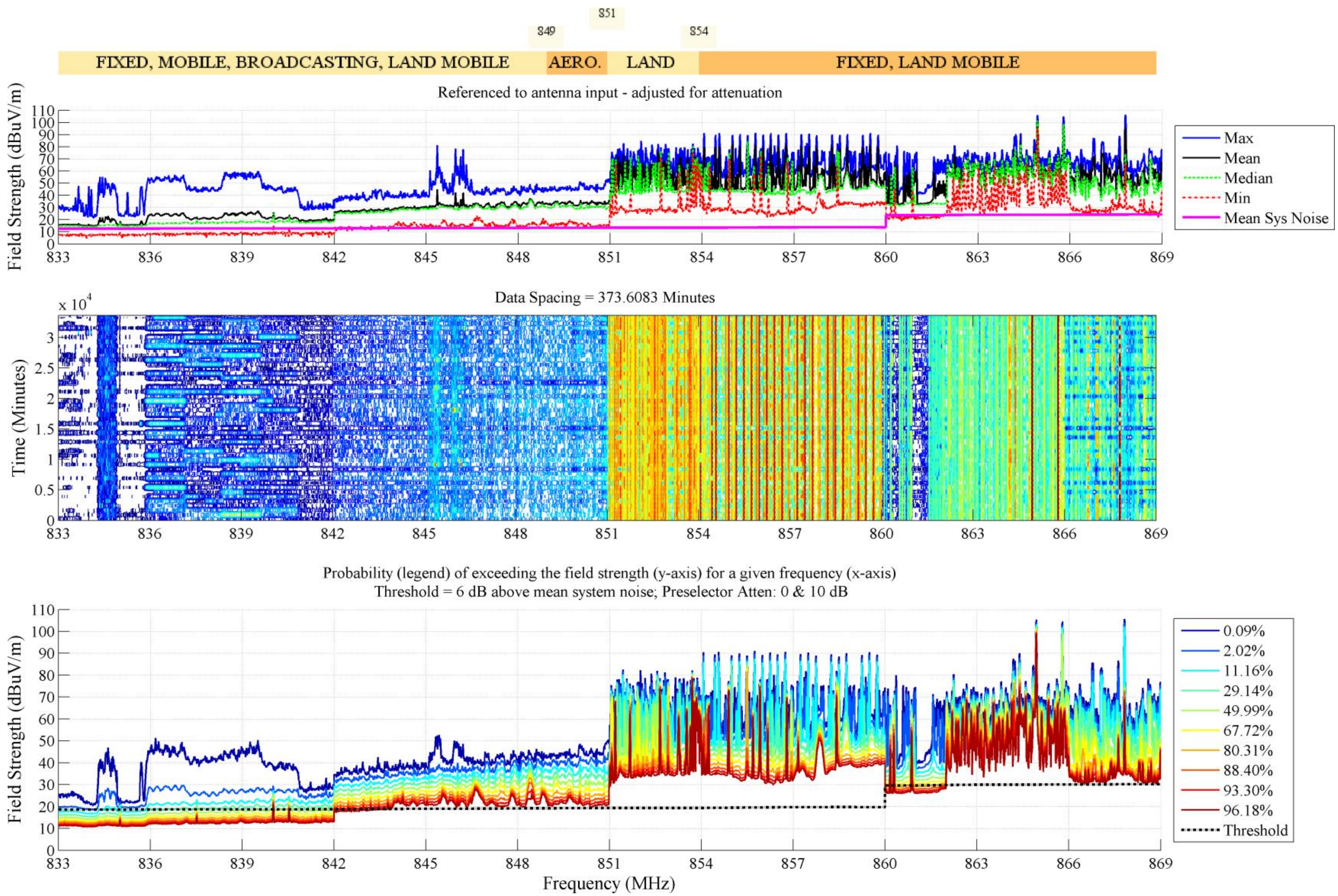

Figure 62. NTIA spectrum survey results from 833 to 869 MHz in Denver, CO, 2011.

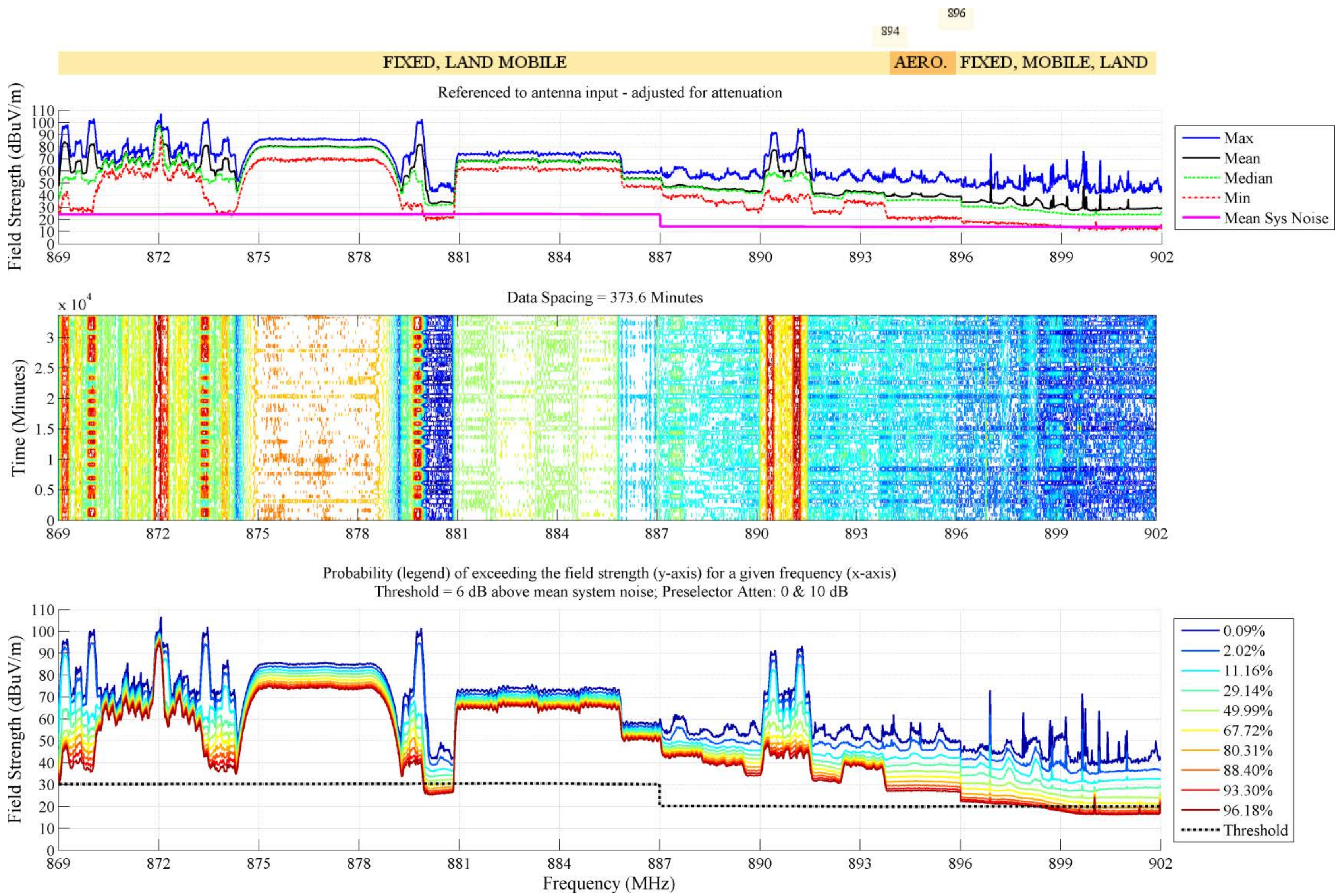

Figure 63. NTIA spectrum survey results from 869 to 902 MHz in Denver, CO, 2011.

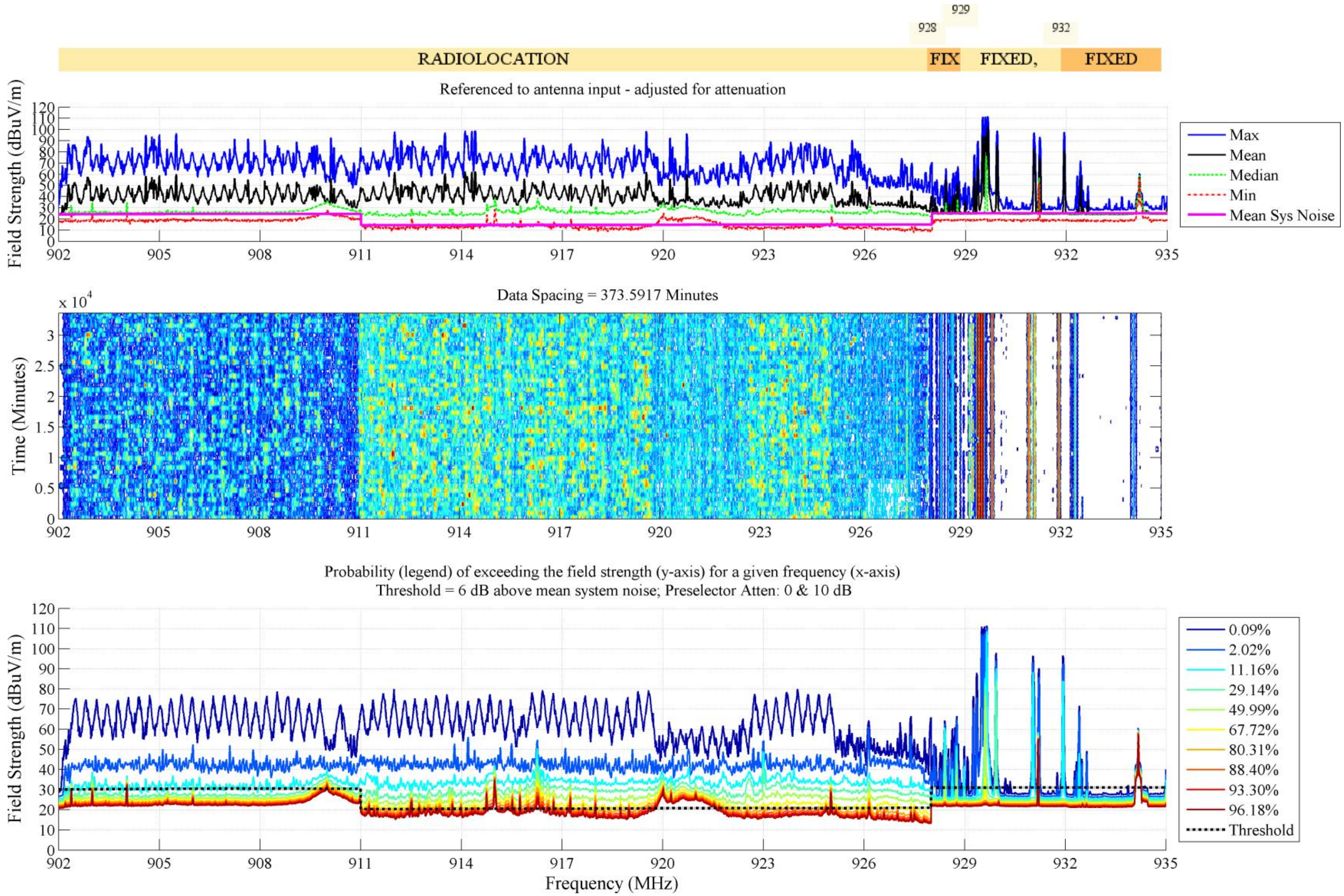

Figure 64. NTIA spectrum survey results from 902 to 935 MHz in Denver, CO, 2011.

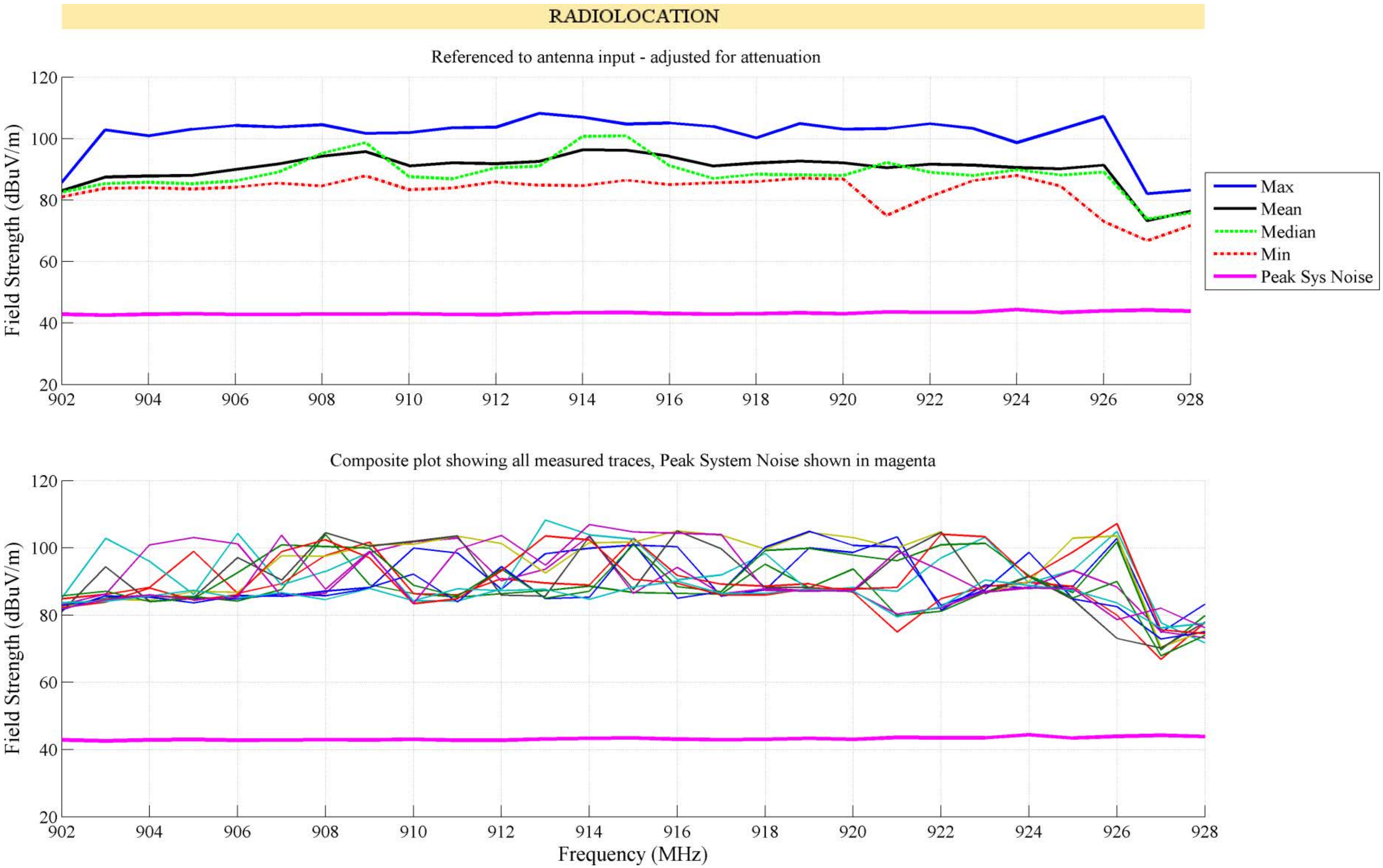

Figure 65. NTIA spectrum survey results from 902 to 928 MHz in Denver, CO, 2011. This measurement was taken using the stepped-spectrum measurement algorithm.

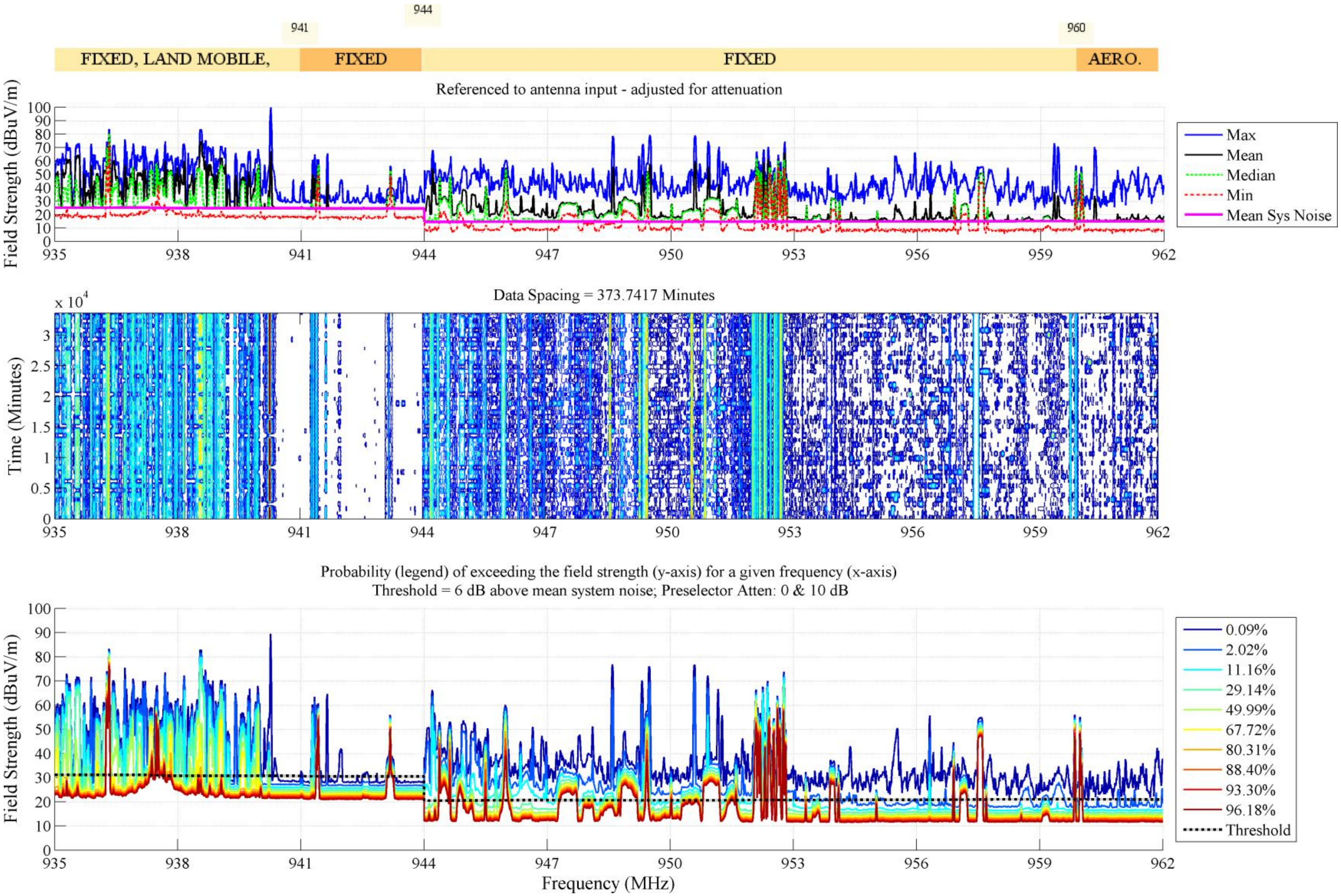

Figure 66. NTIA spectrum survey results from 935 to 962 MHz in Denver, CO, 2011.

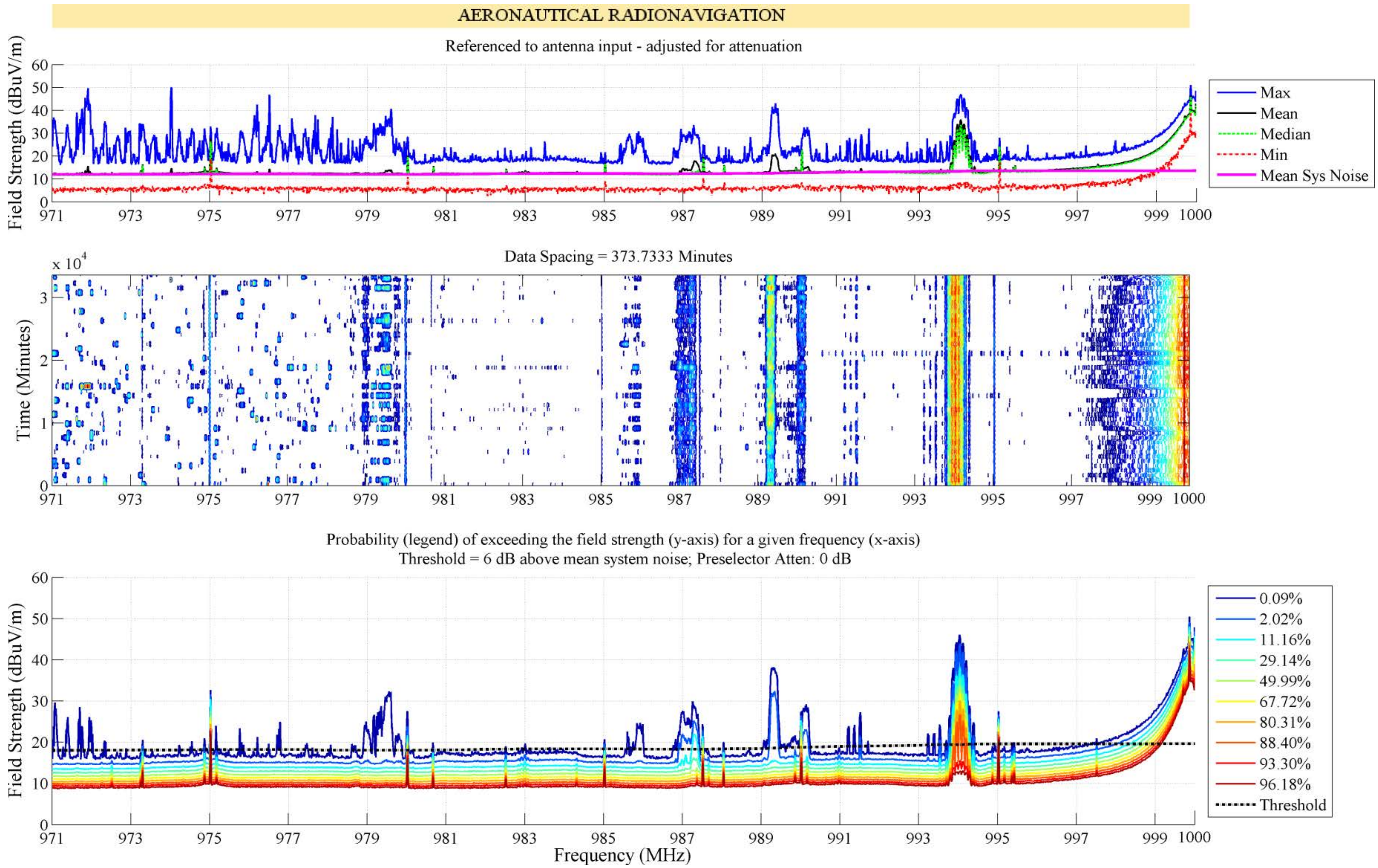

Figure 67. NTIA spectrum survey results from 971 to 1000 MHz in Denver, CO, 2011.

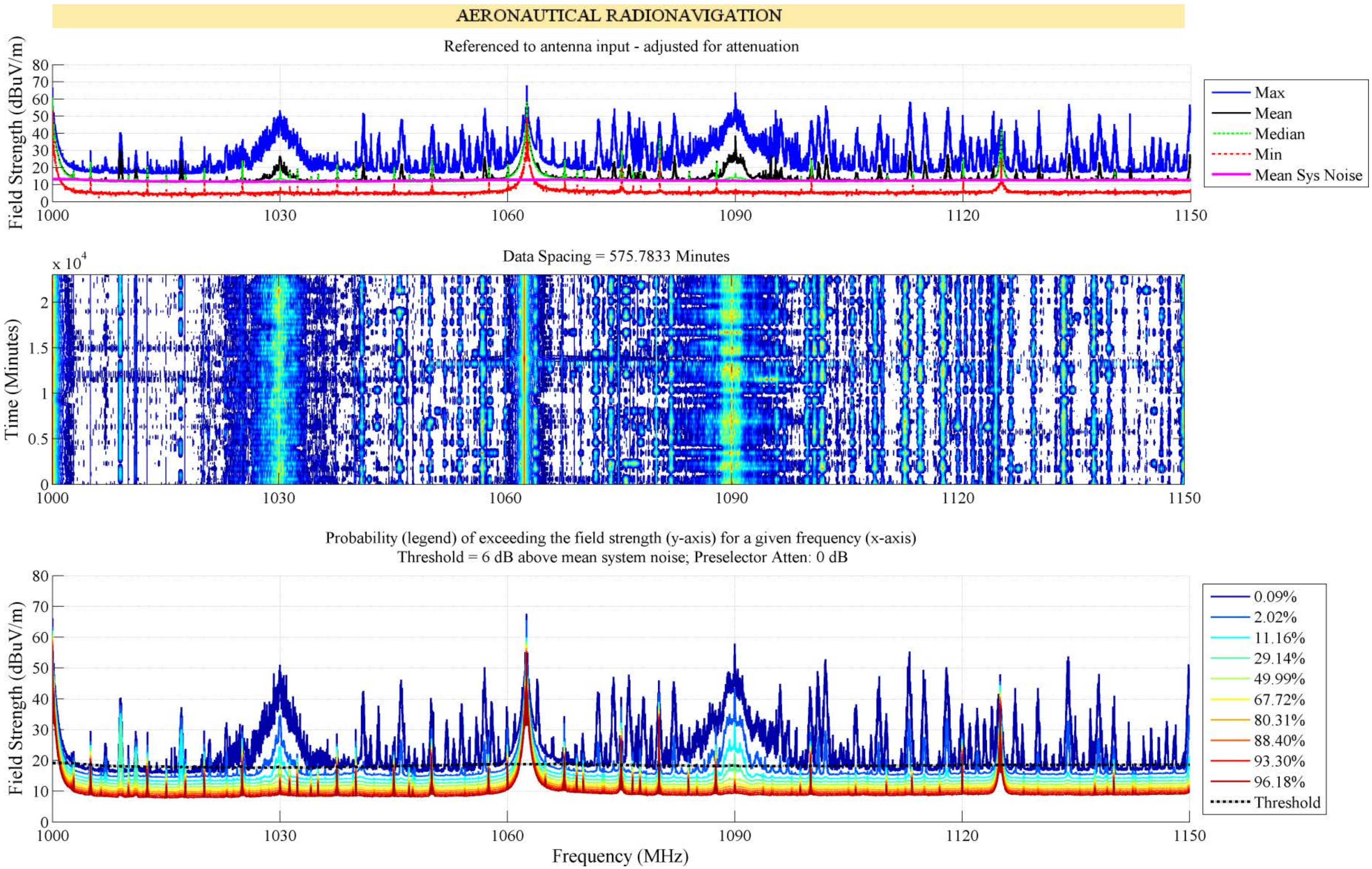

Figure 68. NTIA spectrum survey results from 1000 to 1150 MHz in Denver, CO, 2011.

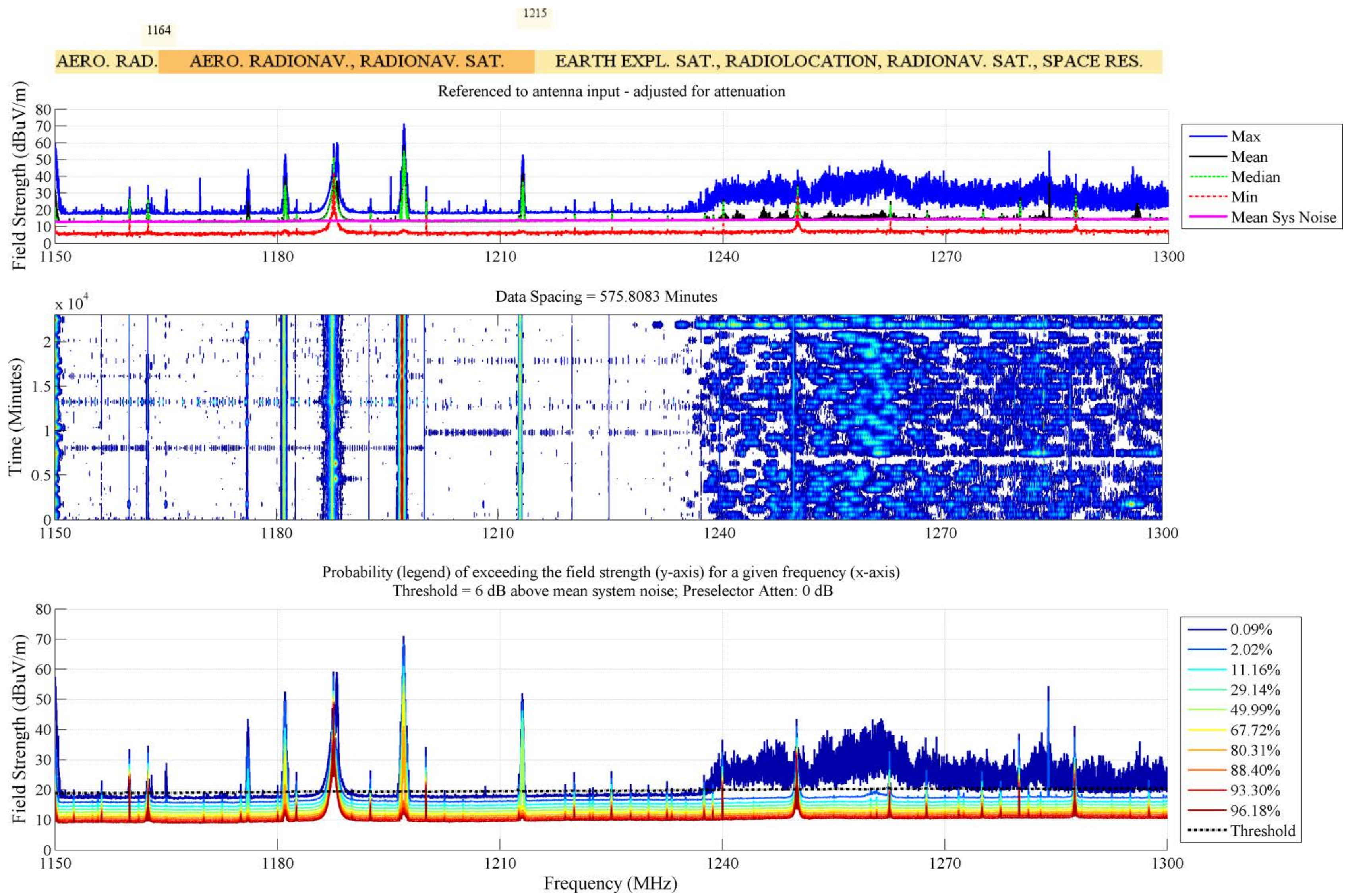

Figure 69. NTIA spectrum survey results from 1150 to 1300 MHz in Denver, CO, 2011.

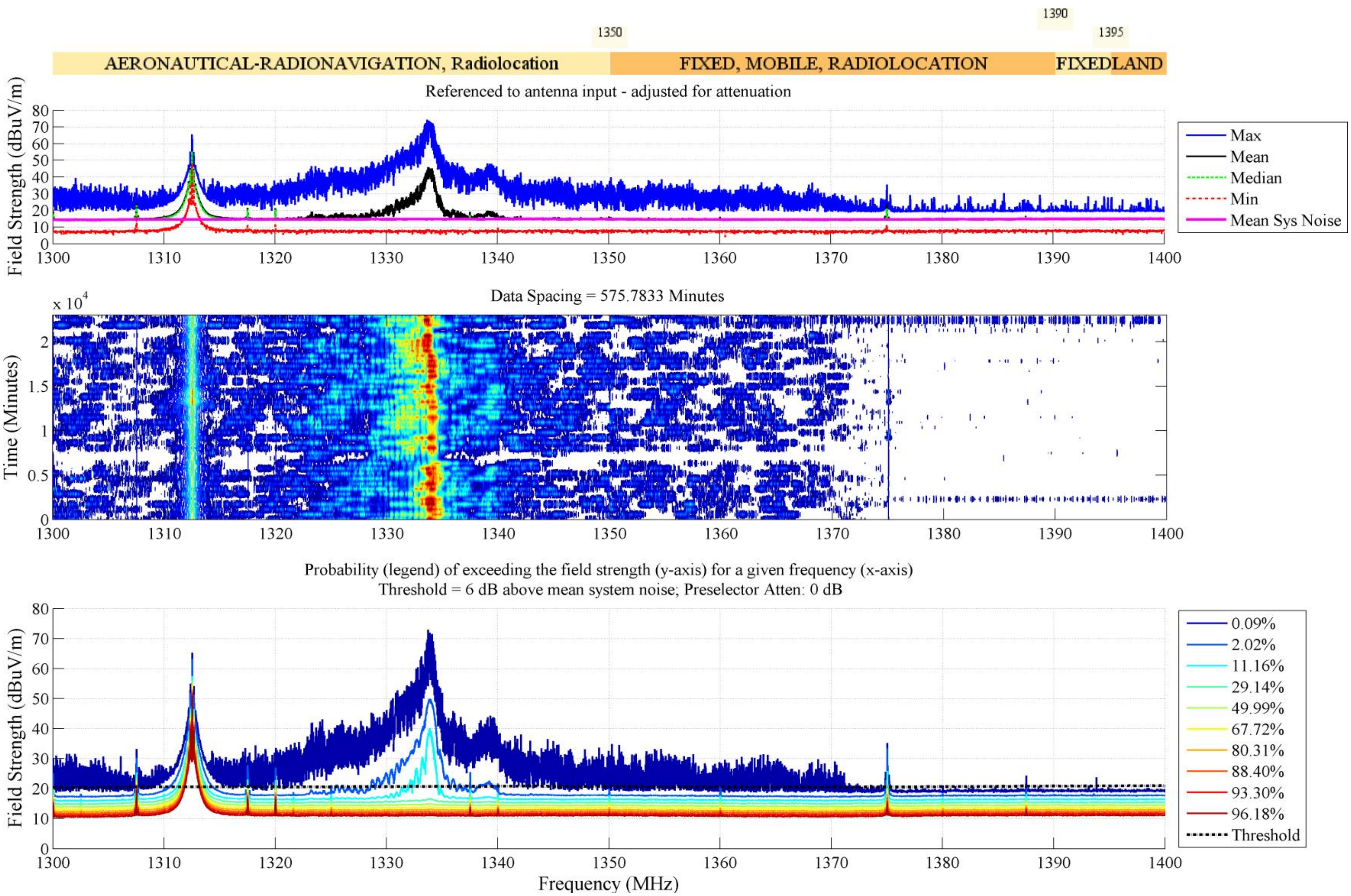

Figure 70. NTIA spectrum survey results from 1300 to 1400 MHz in Denver, CO, 2011.

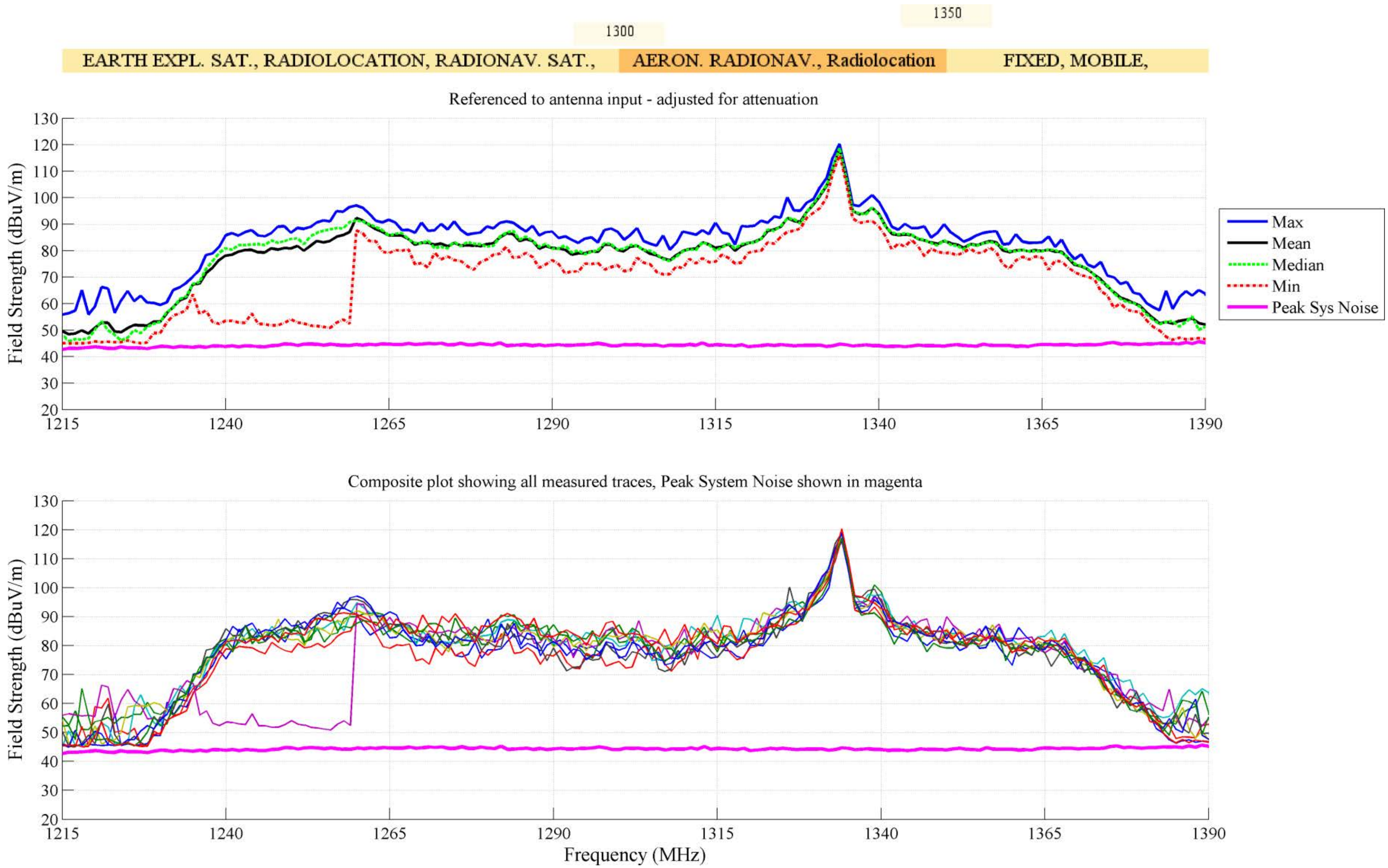

Figure 71. NTIA spectrum survey results from 1215 to 1390 MHz in Denver, CO, 2011. This measurement was taken using the stepped-spectrum measurement algorithm.

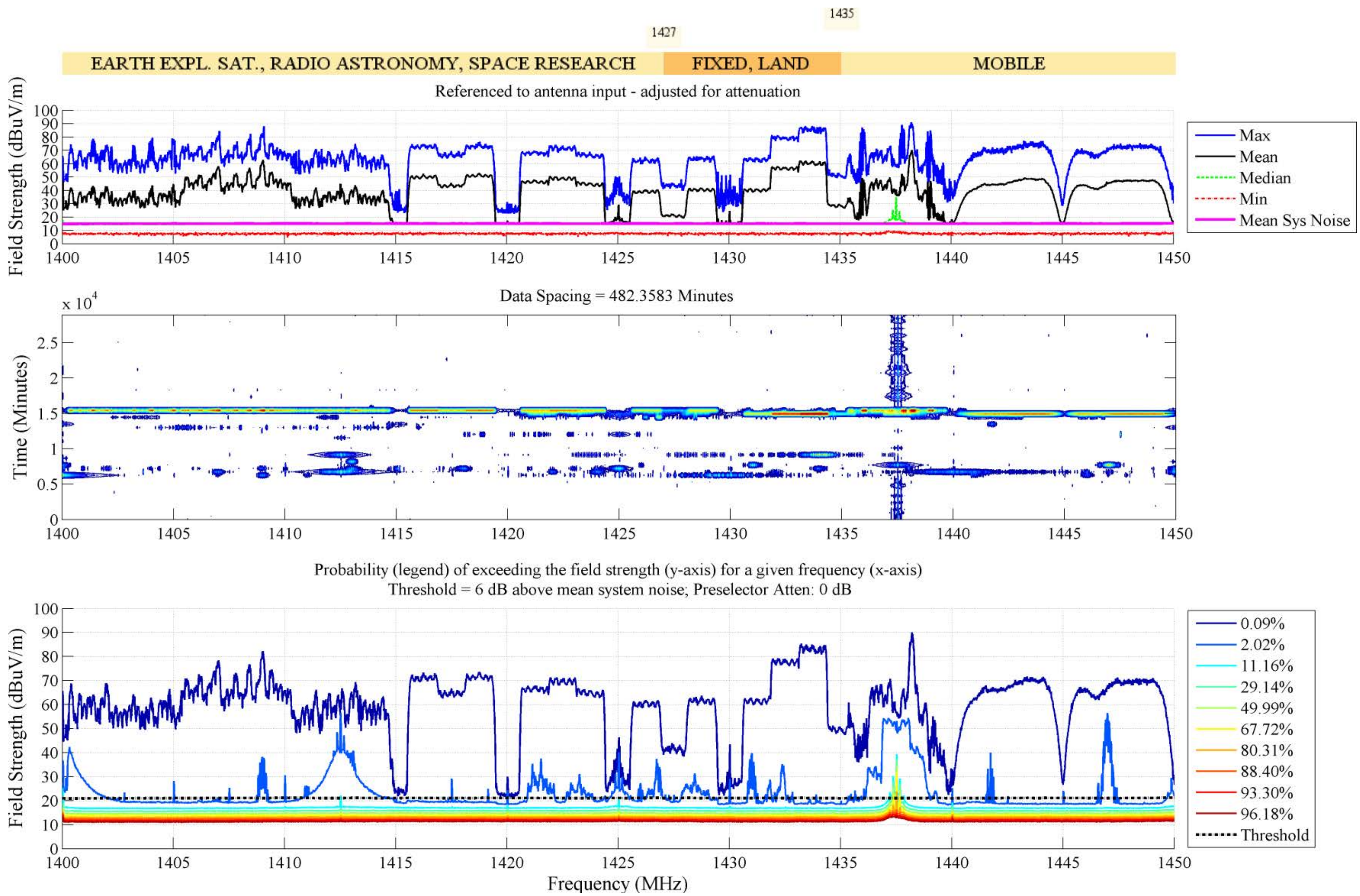

Figure 72. NTIA spectrum survey results from 1400 to 1450 MHz in Denver, CO, 2011.

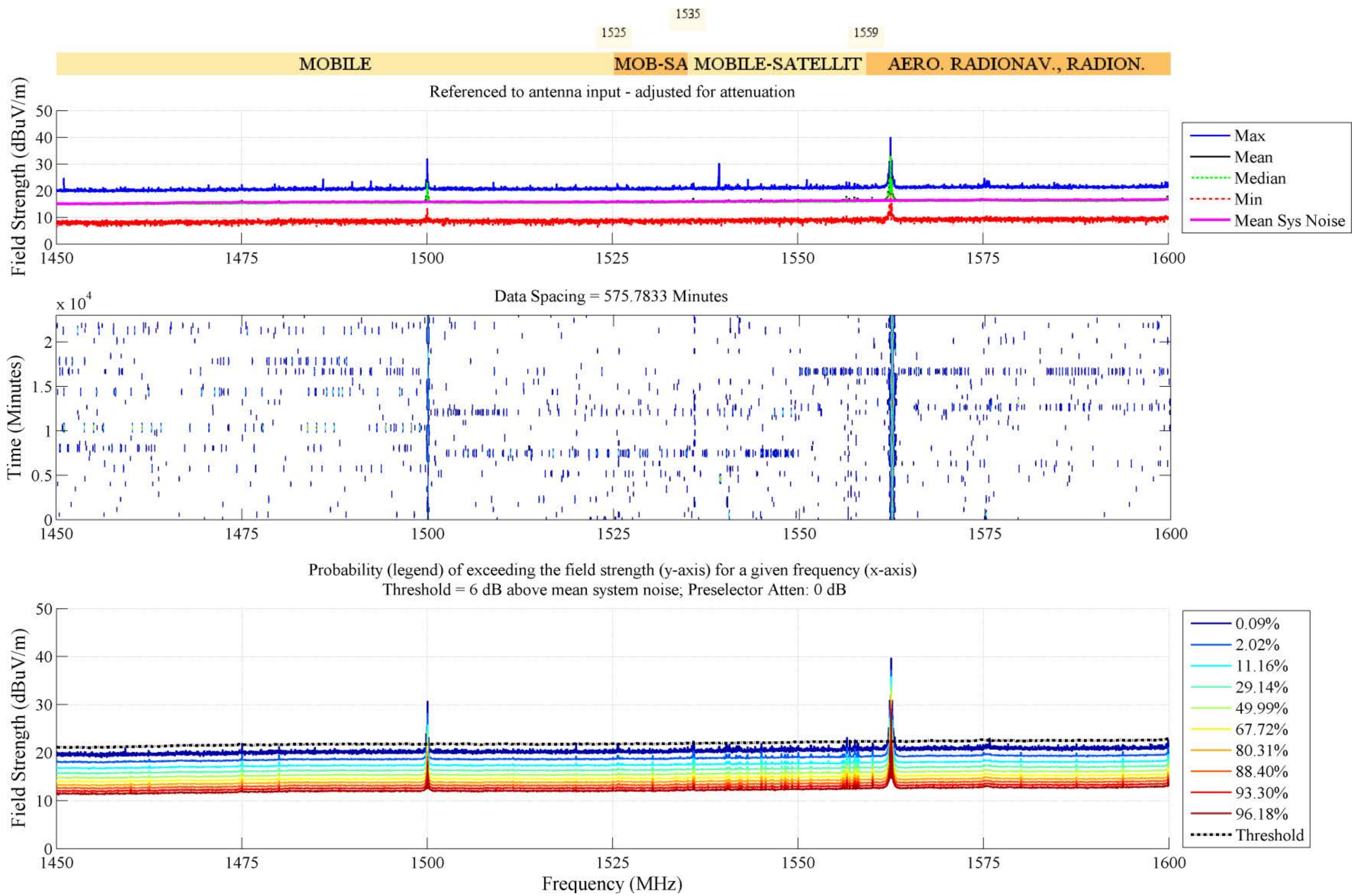

Figure 73. NTIA spectrum survey results from 1450 to 1600 MHz in Denver, CO, 2011.

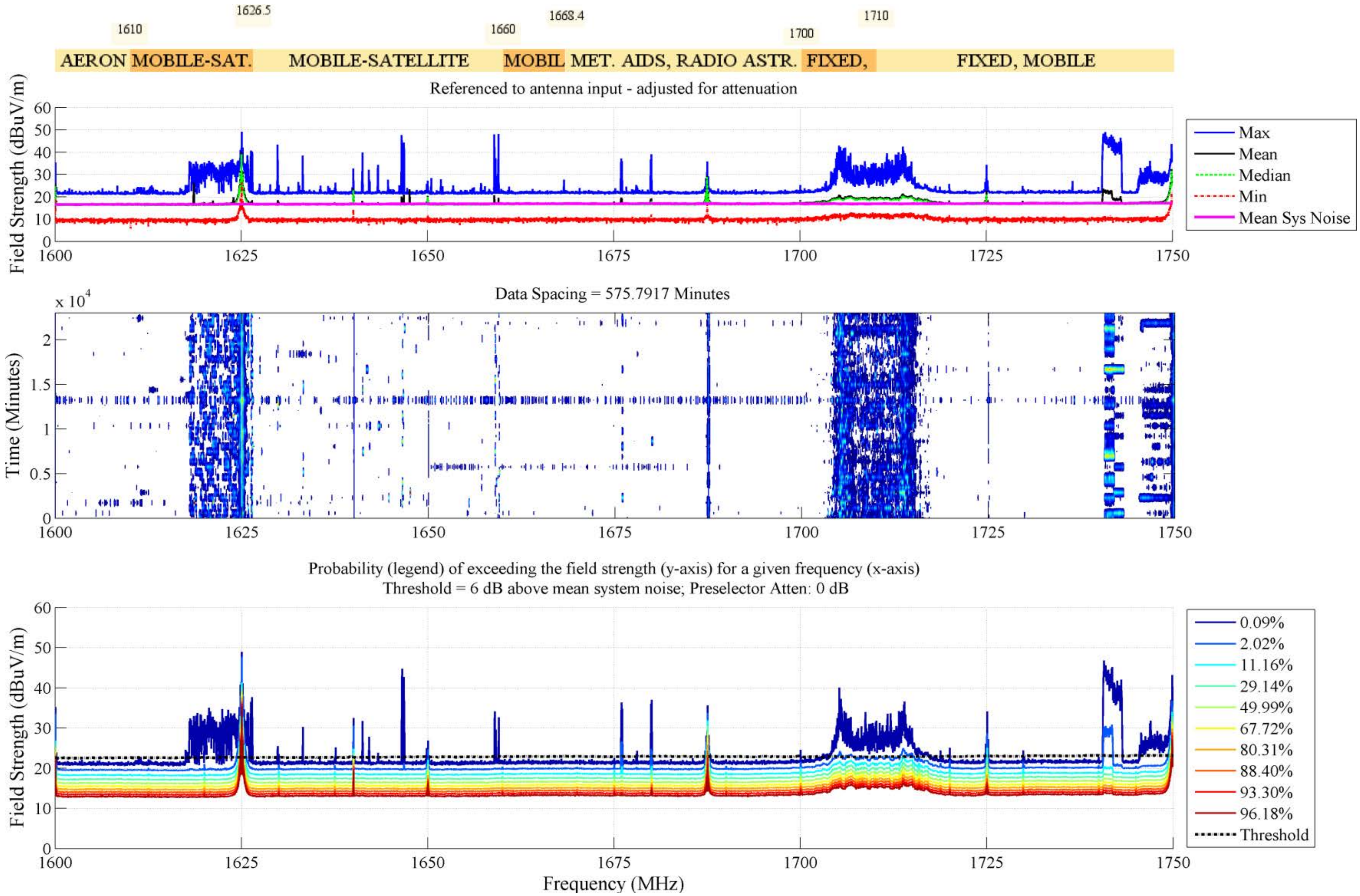

Figure 74. NTIA spectrum survey results from 1600 to 1750 MHz in Denver, CO, 2011.

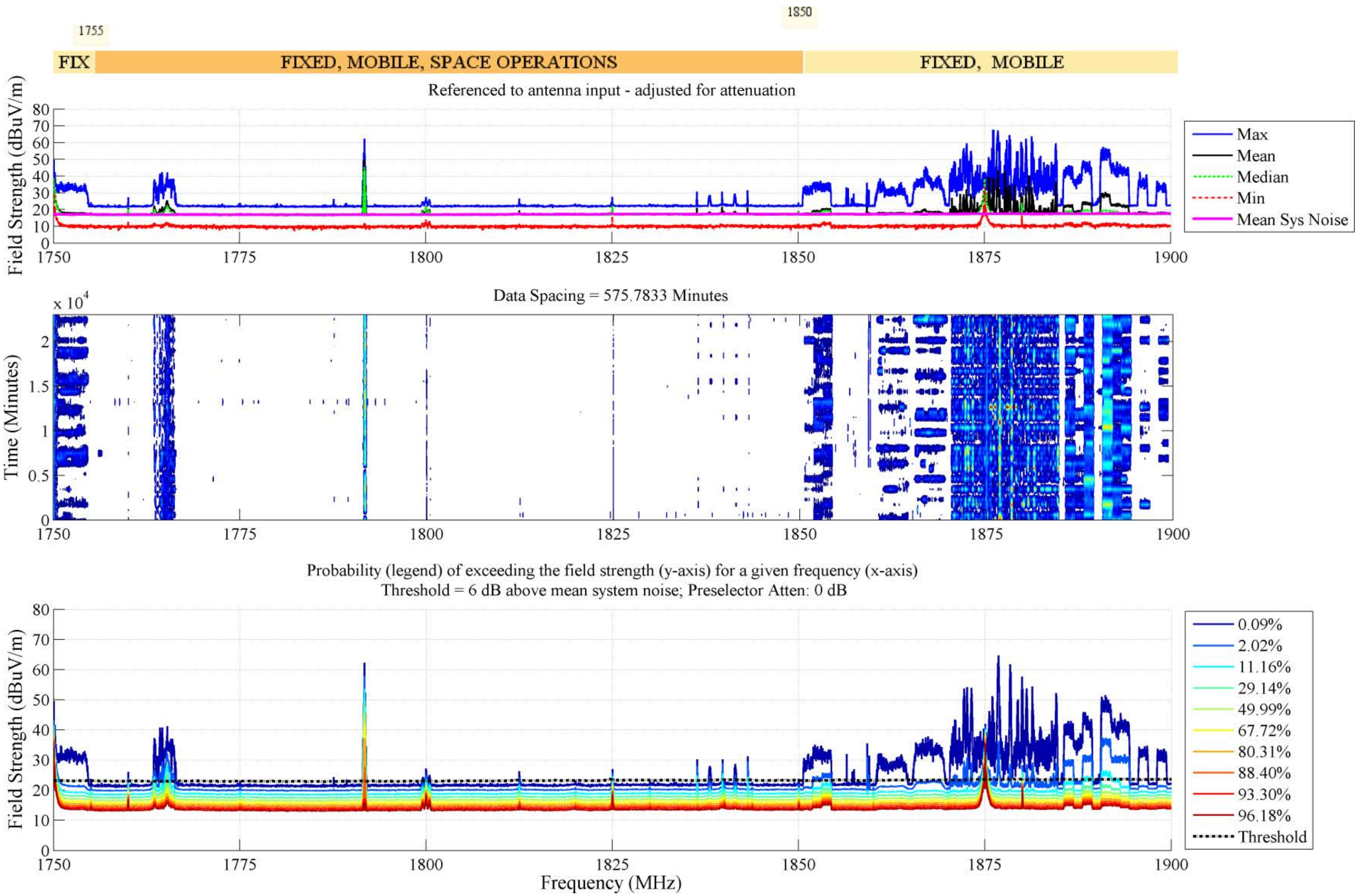

Figure 75. NTIA spectrum survey results from 1750 to 1900 MHz in Denver, CO, 2011.

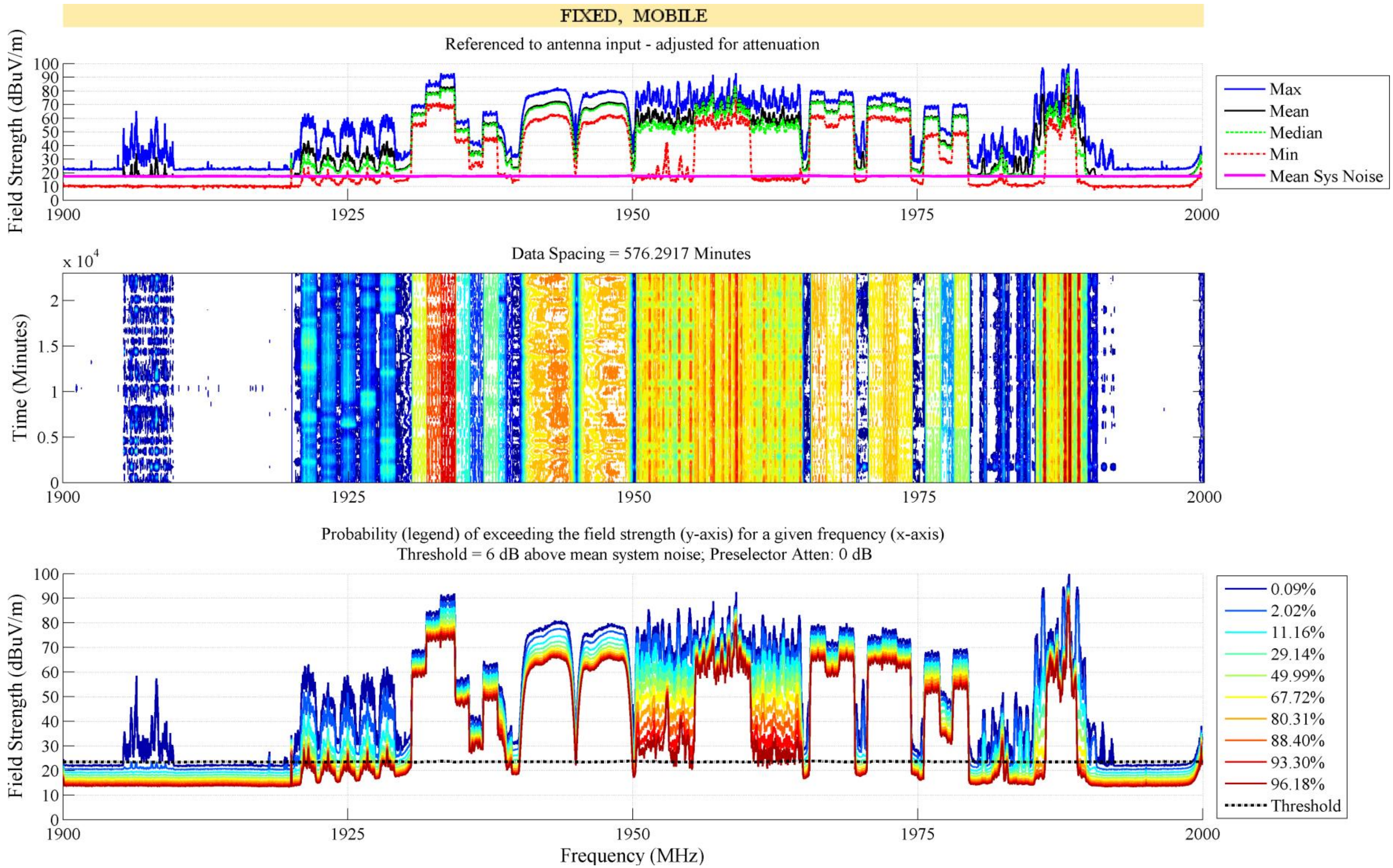

Figure 76. NTIA spectrum survey results from 1900 to 2000 MHz in Denver, CO, 2011.

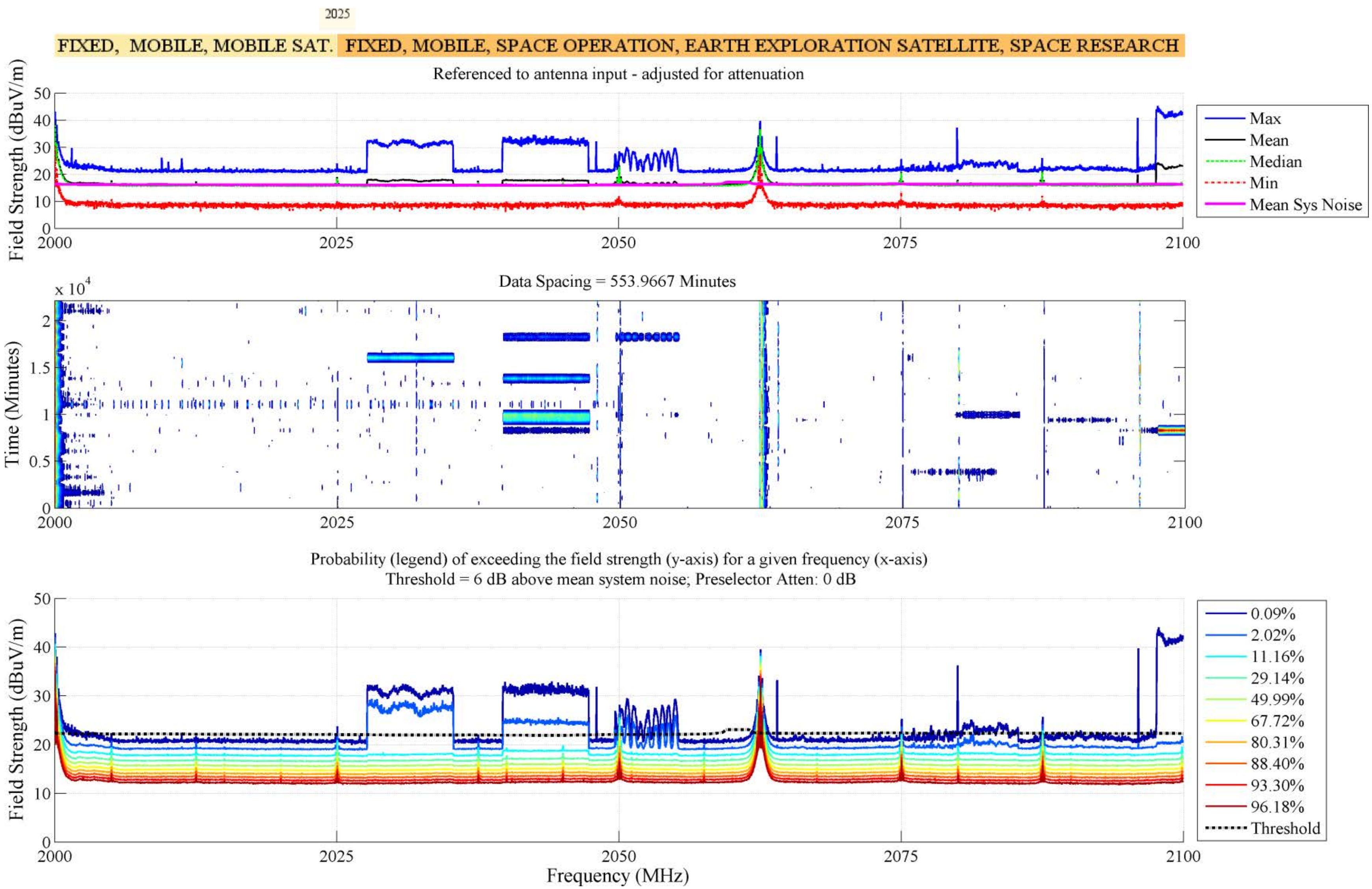

Figure 77. NTIA spectrum survey results from 2000 to 2100 MHz in Denver, CO, 2011.

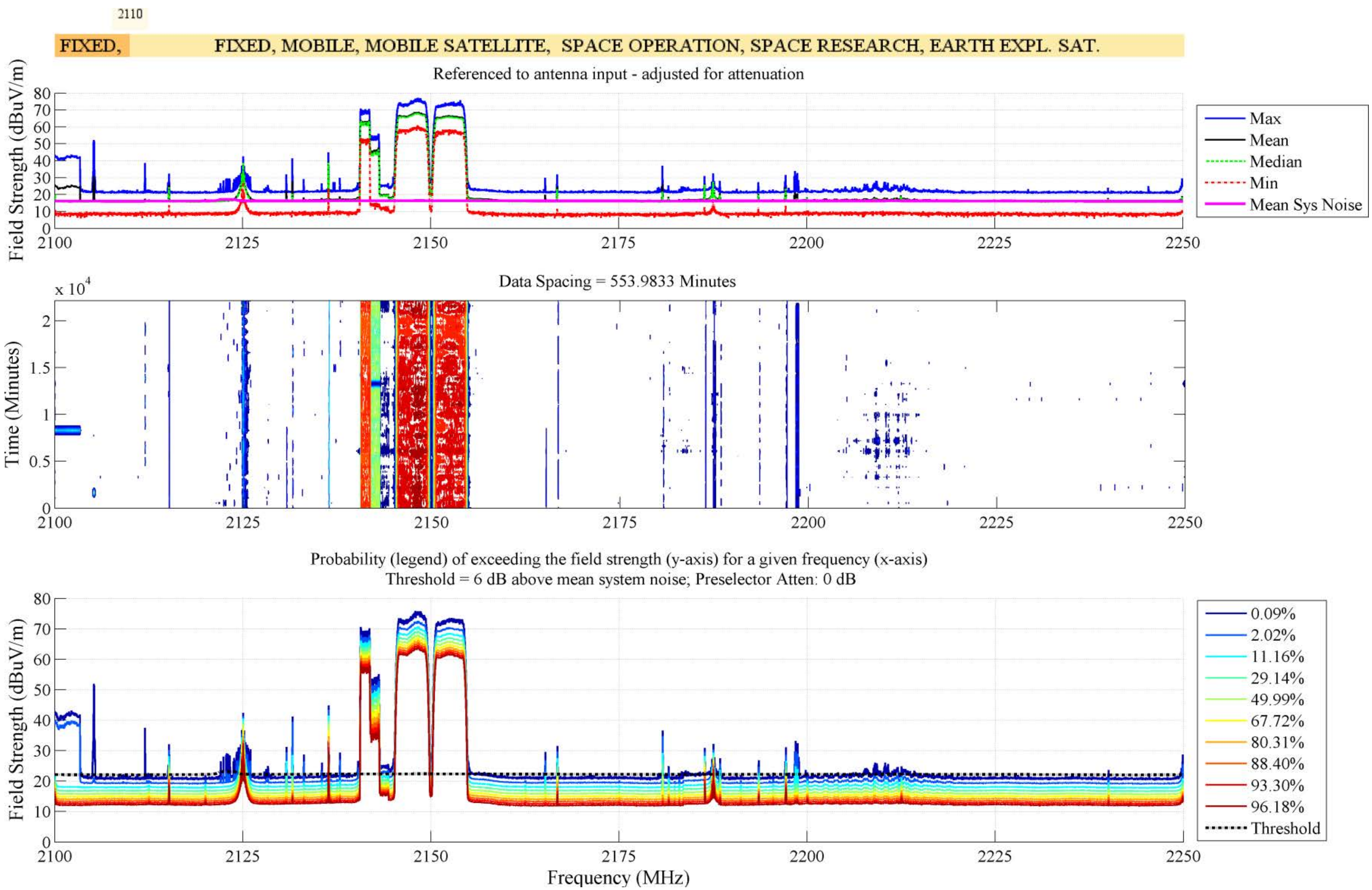

Figure 78. NTIA spectrum survey results from 2100 to 2250 MHz in Denver, CO, 2011.

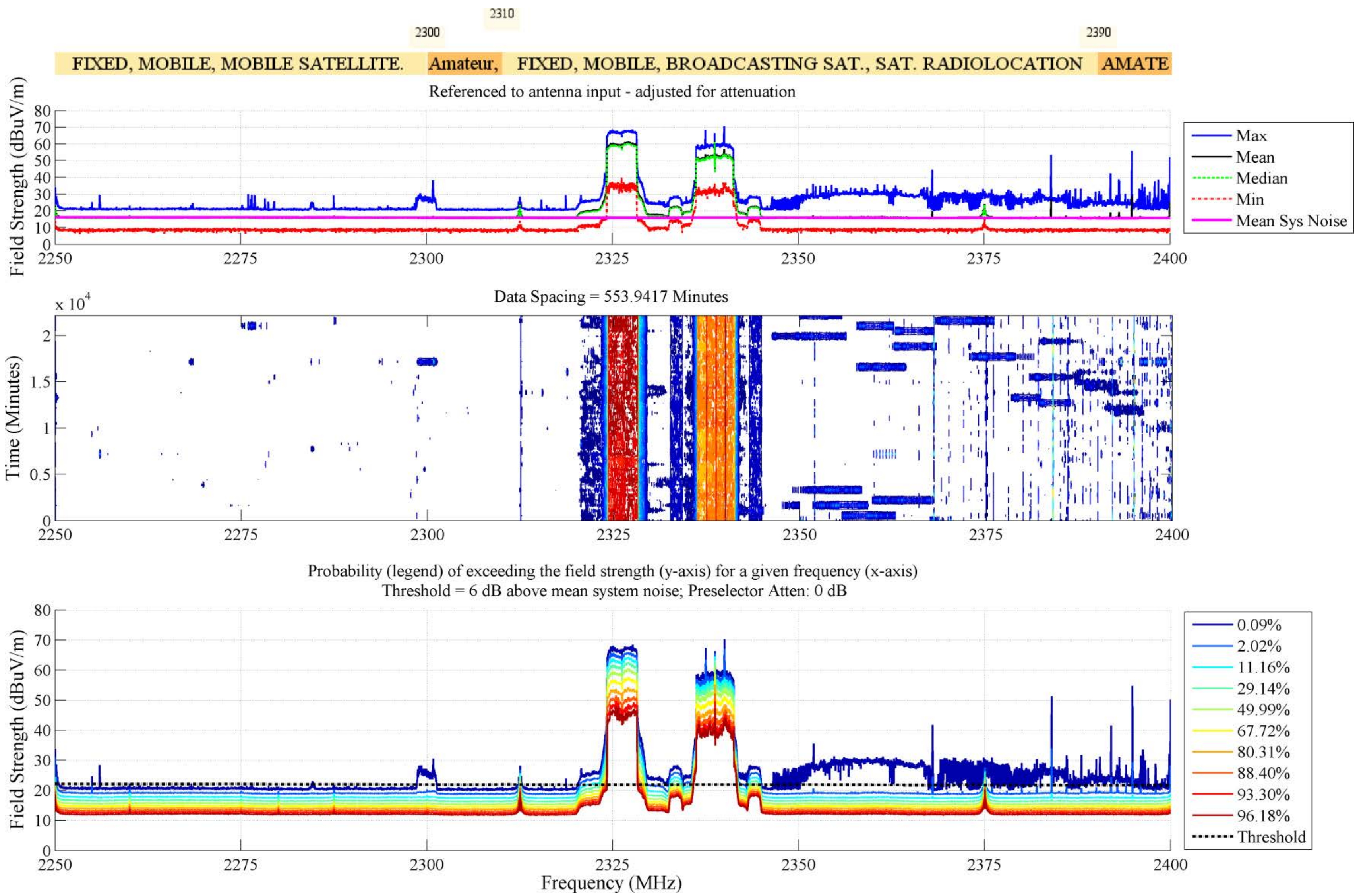

Figure 79. NTIA spectrum survey results from 2250 to 2400 MHz in Denver, CO, 2011.

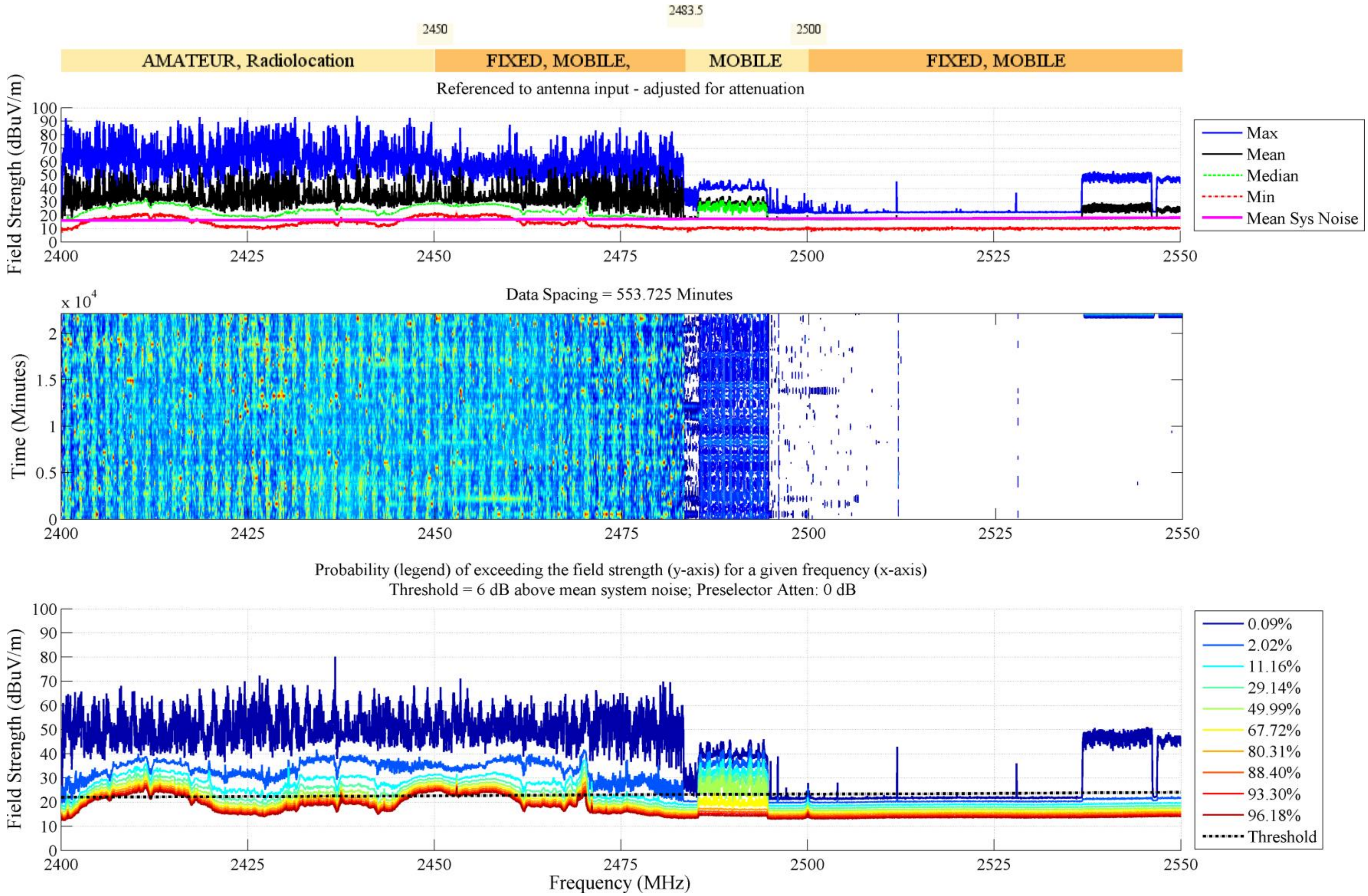

Figure 80. NTIA spectrum survey results from 2400 to 2550 MHz in Denver, CO, 2011.

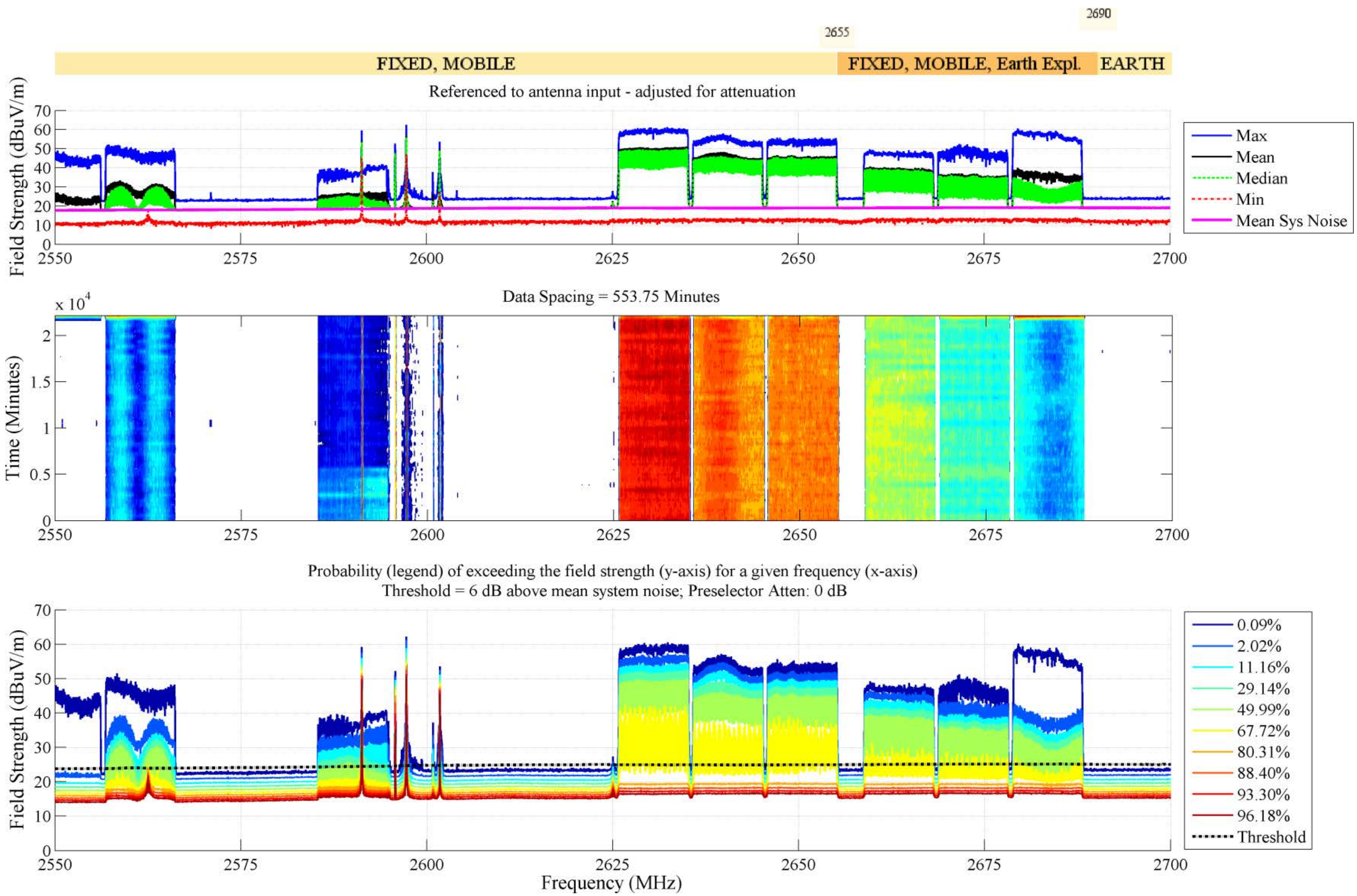

Figure 81. NTIA spectrum survey results from 2550 to 2700 MHz in Denver, CO, 2011.

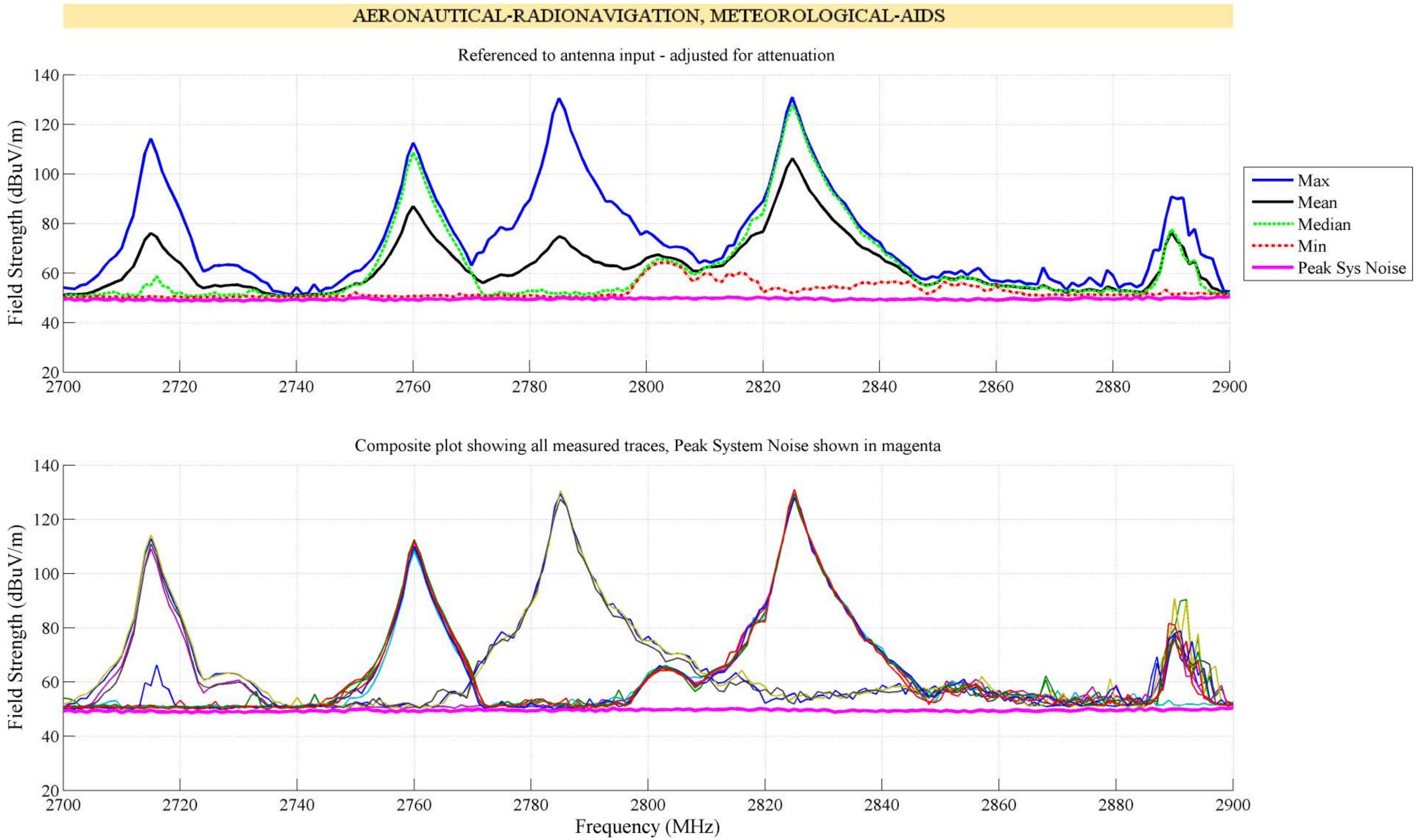

Figure 82. NTIA spectrum survey results from 2700 to 2900 MHz in Denver, CO, 2011. This measurement was taken using the stepped-spectrum measurement algorithm.

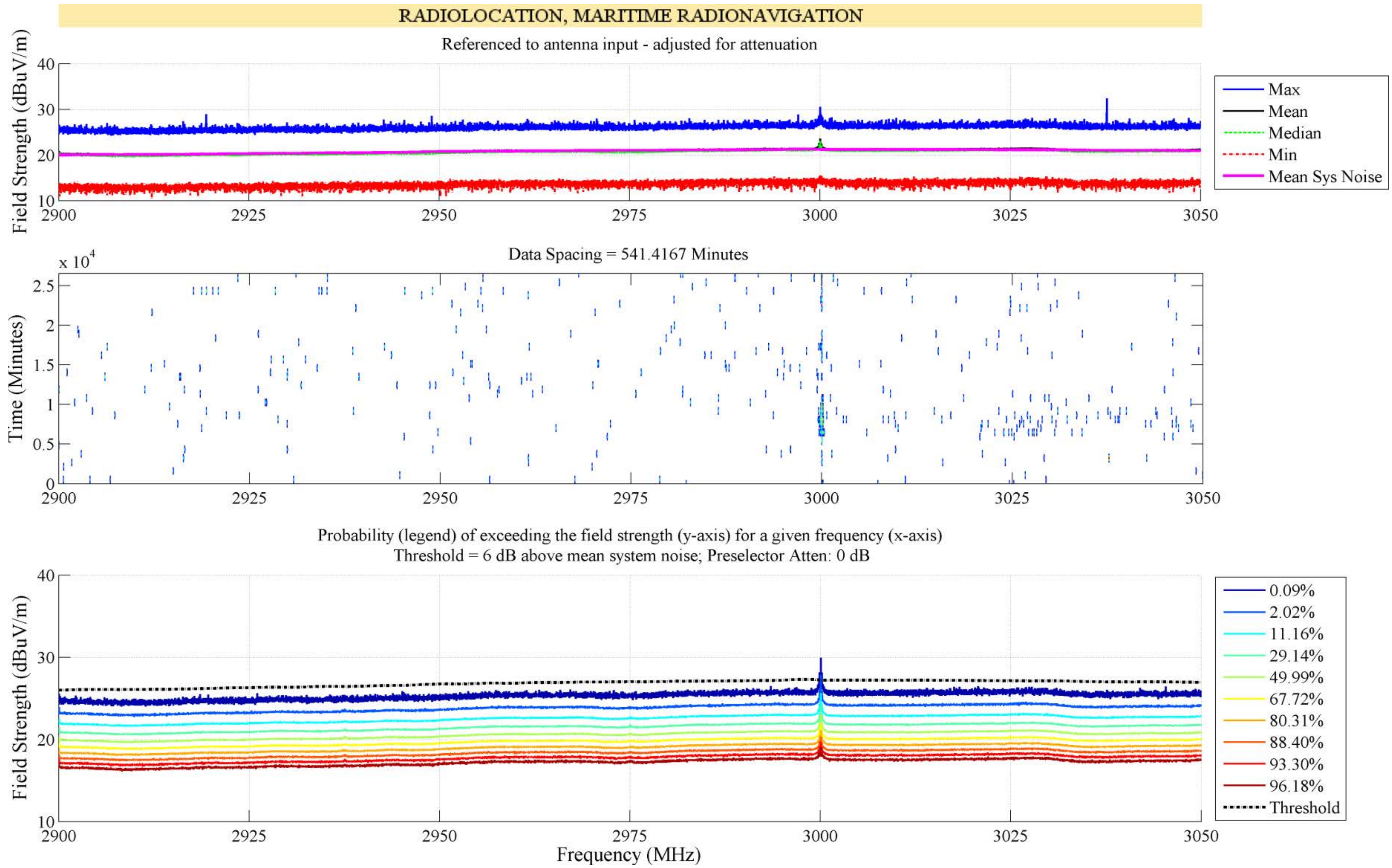

Figure 83. NTIA spectrum survey results from 2900 to 3050 MHz in Denver, CO, 2011.

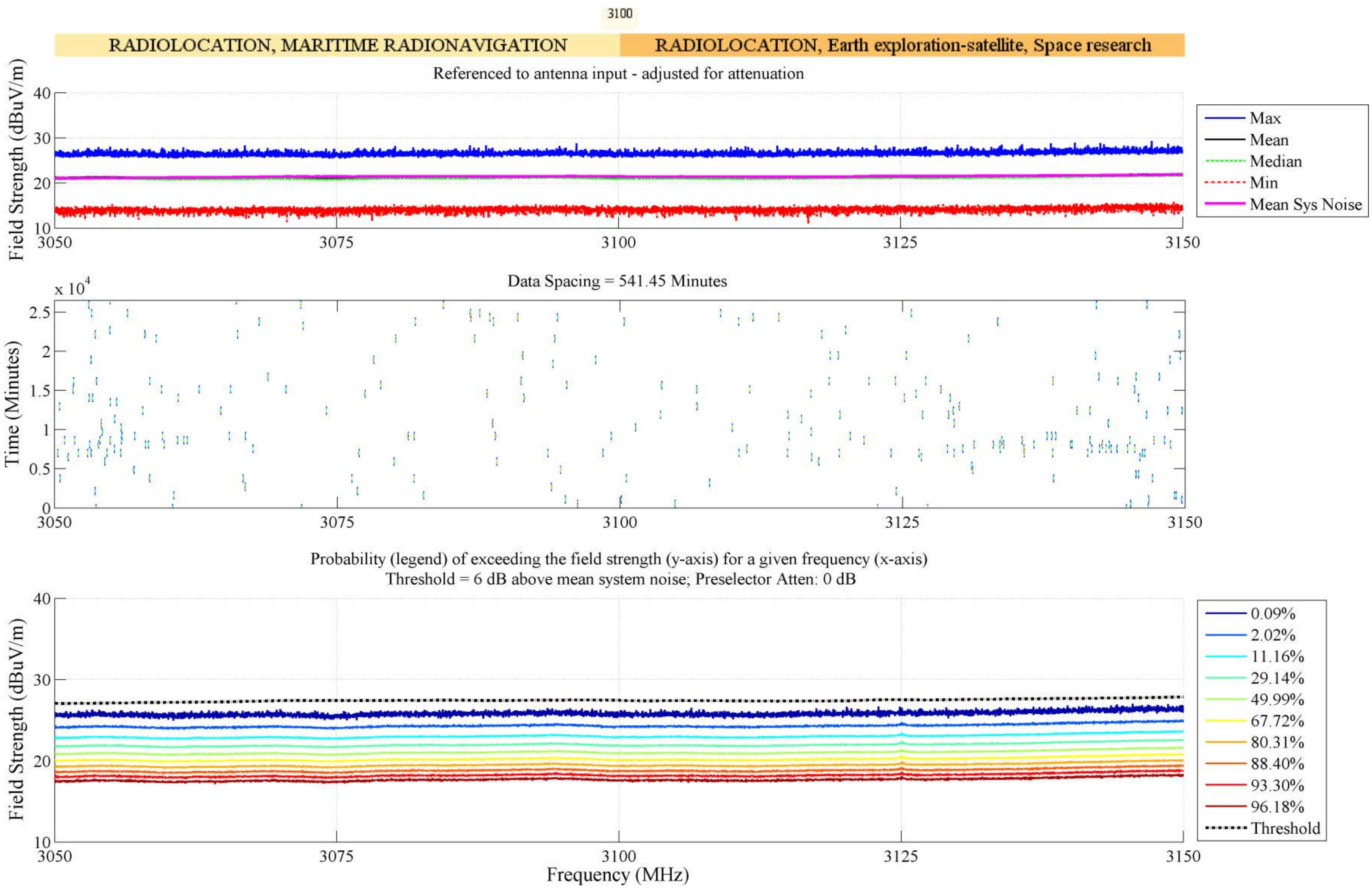

Figure 84. NTIA spectrum survey results from 3050 to 3150 MHz in Denver, CO, 2011.

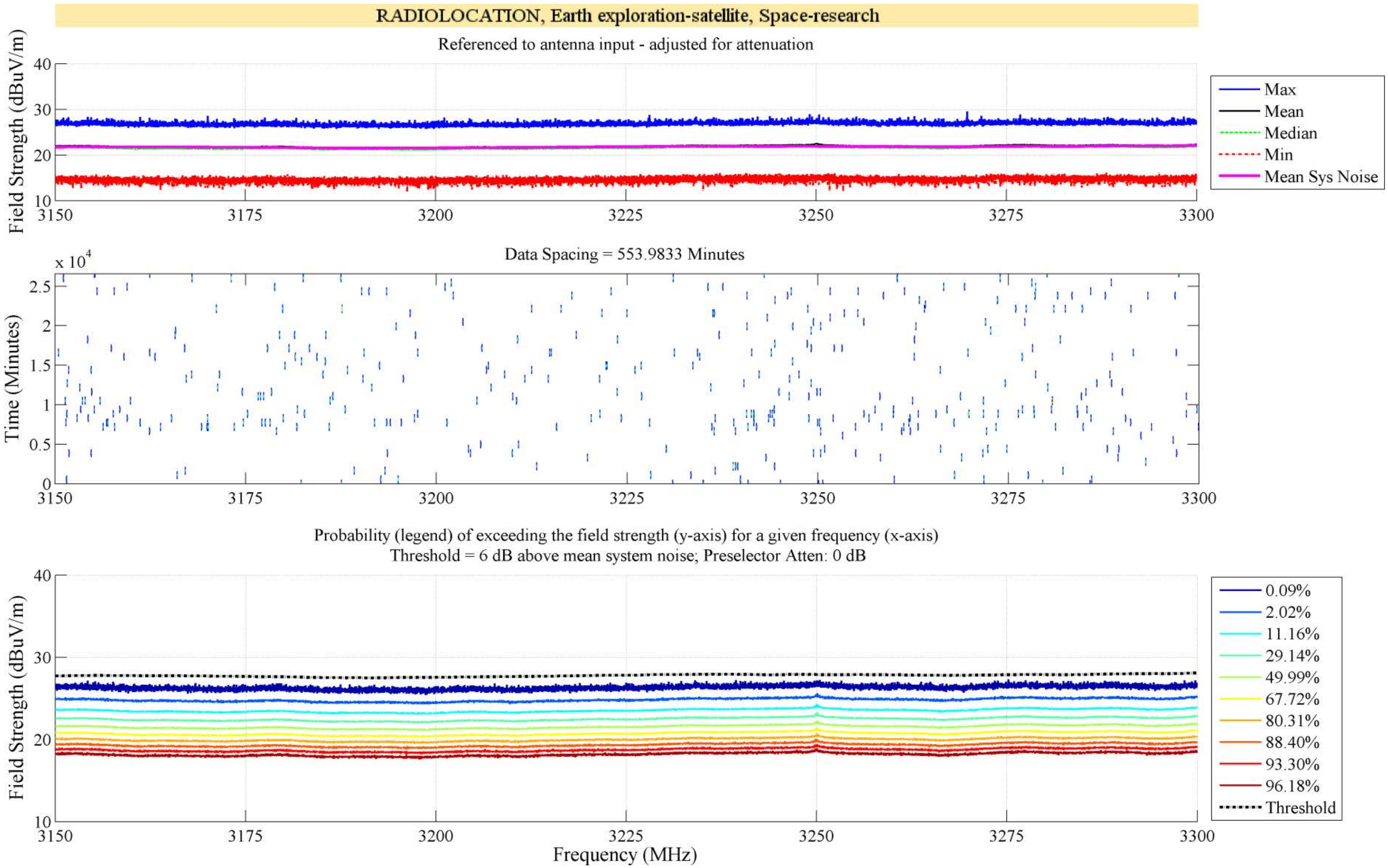

Figure 85. NTIA spectrum survey results from 3150 to 3300 MHz in Denver, CO, 2011.

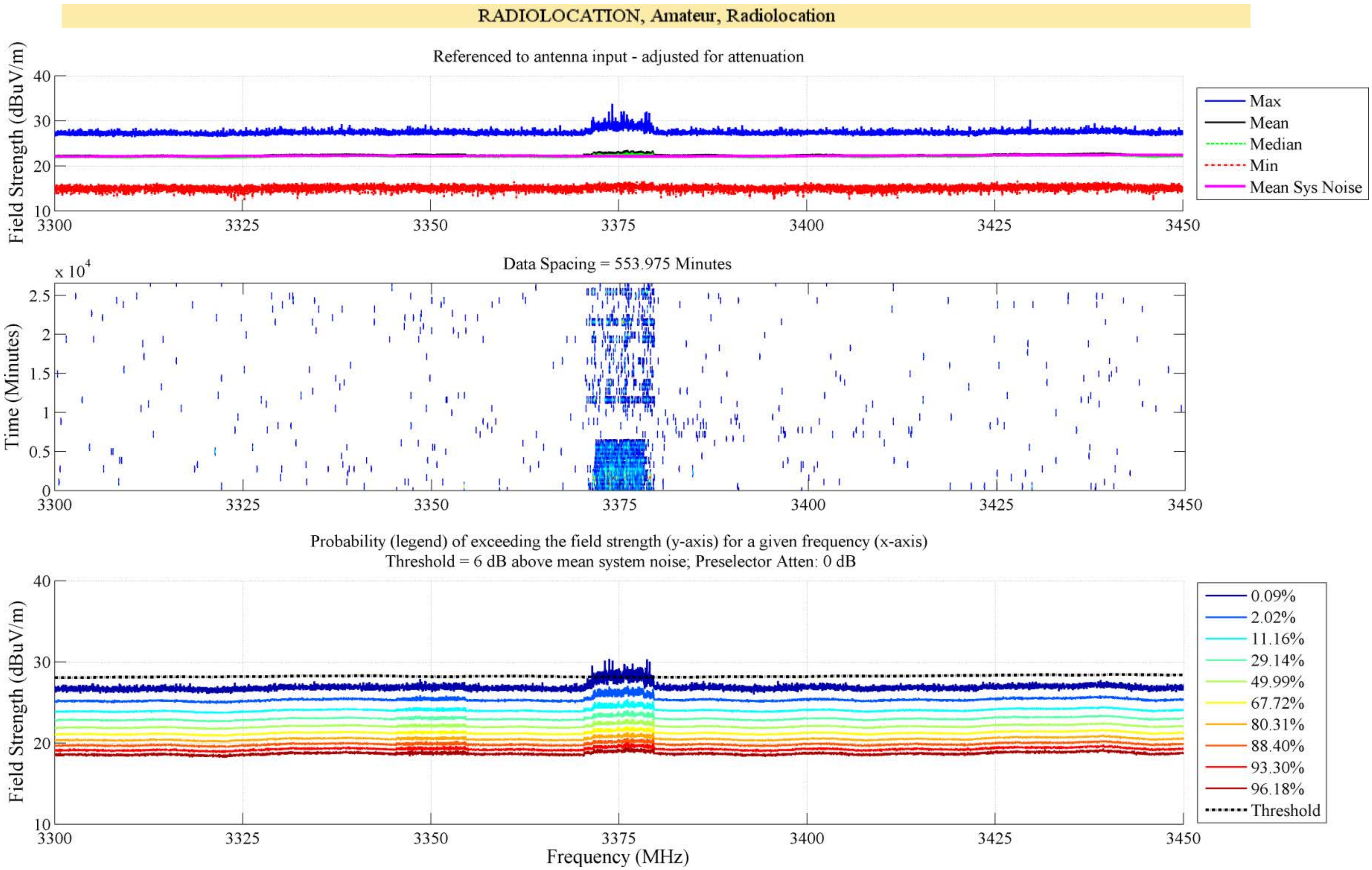

Figure 86. NTIA spectrum survey results from 3300 to 3450 MHz in Denver, CO, 2011.

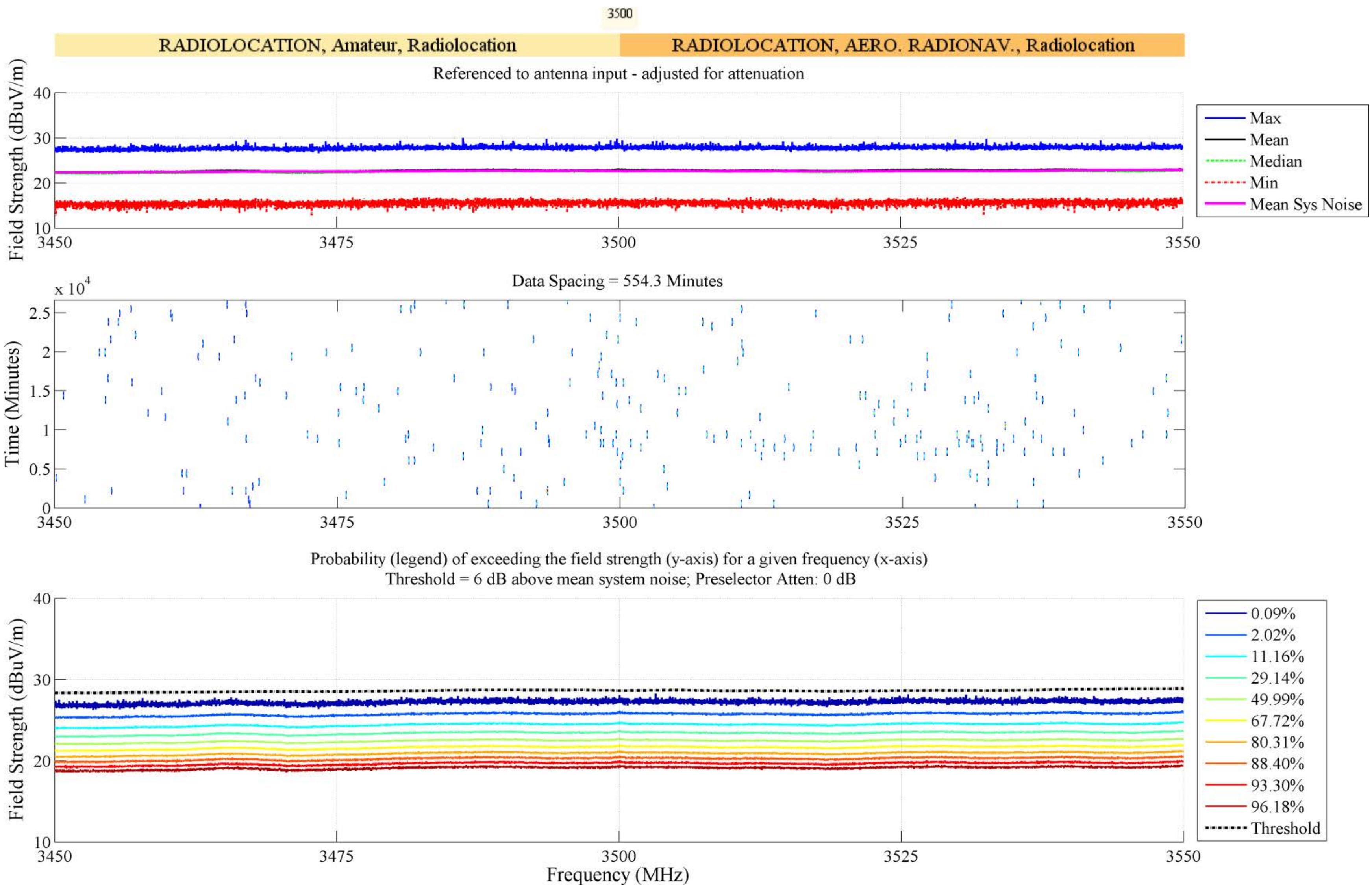

Figure 87. NTIA spectrum survey results from 3450 to 3550 MHz in Denver, CO, 2011.

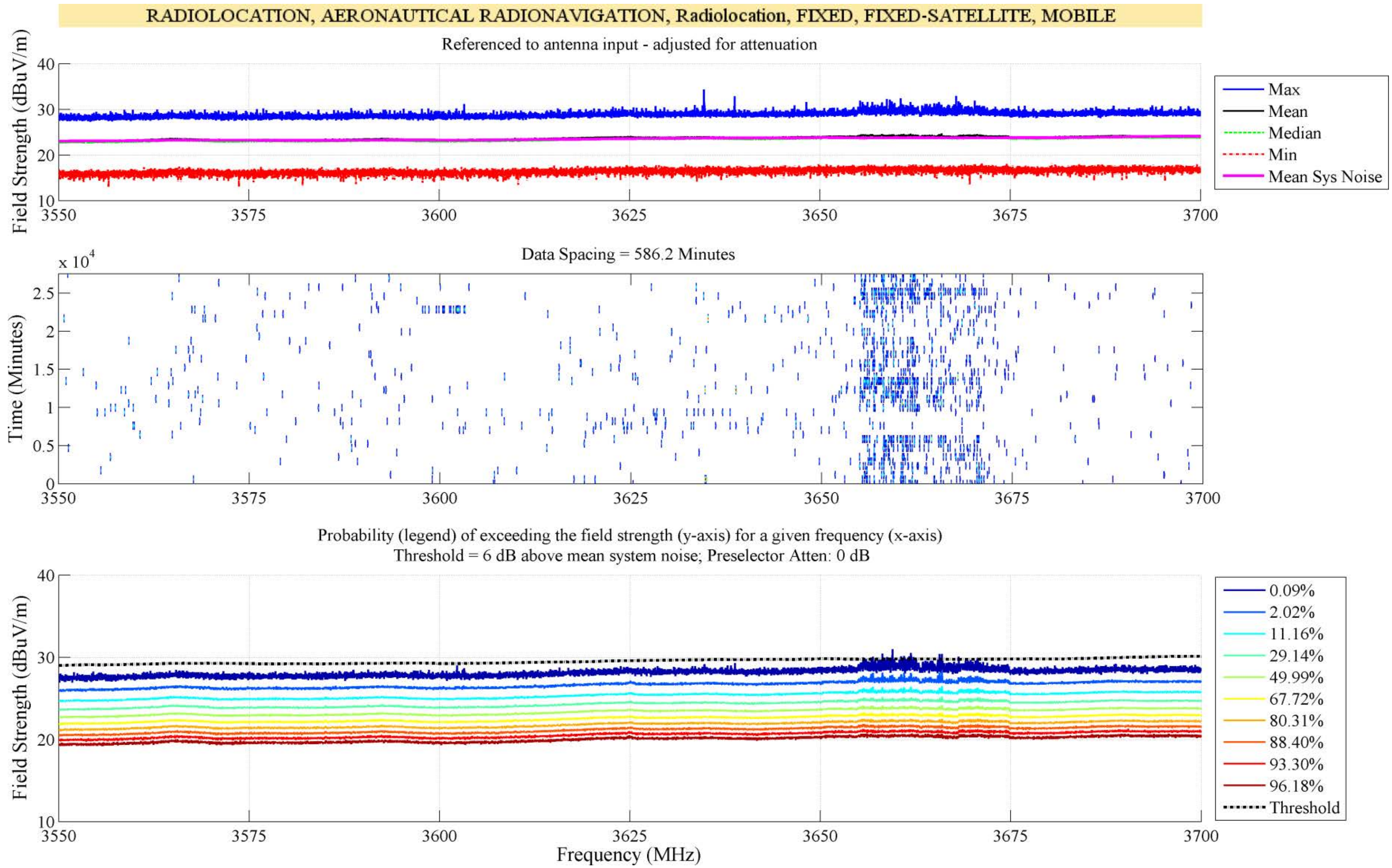

Figure 88. NTIA spectrum survey results from 3550 to 3700 MHz in Denver, CO, 2011.

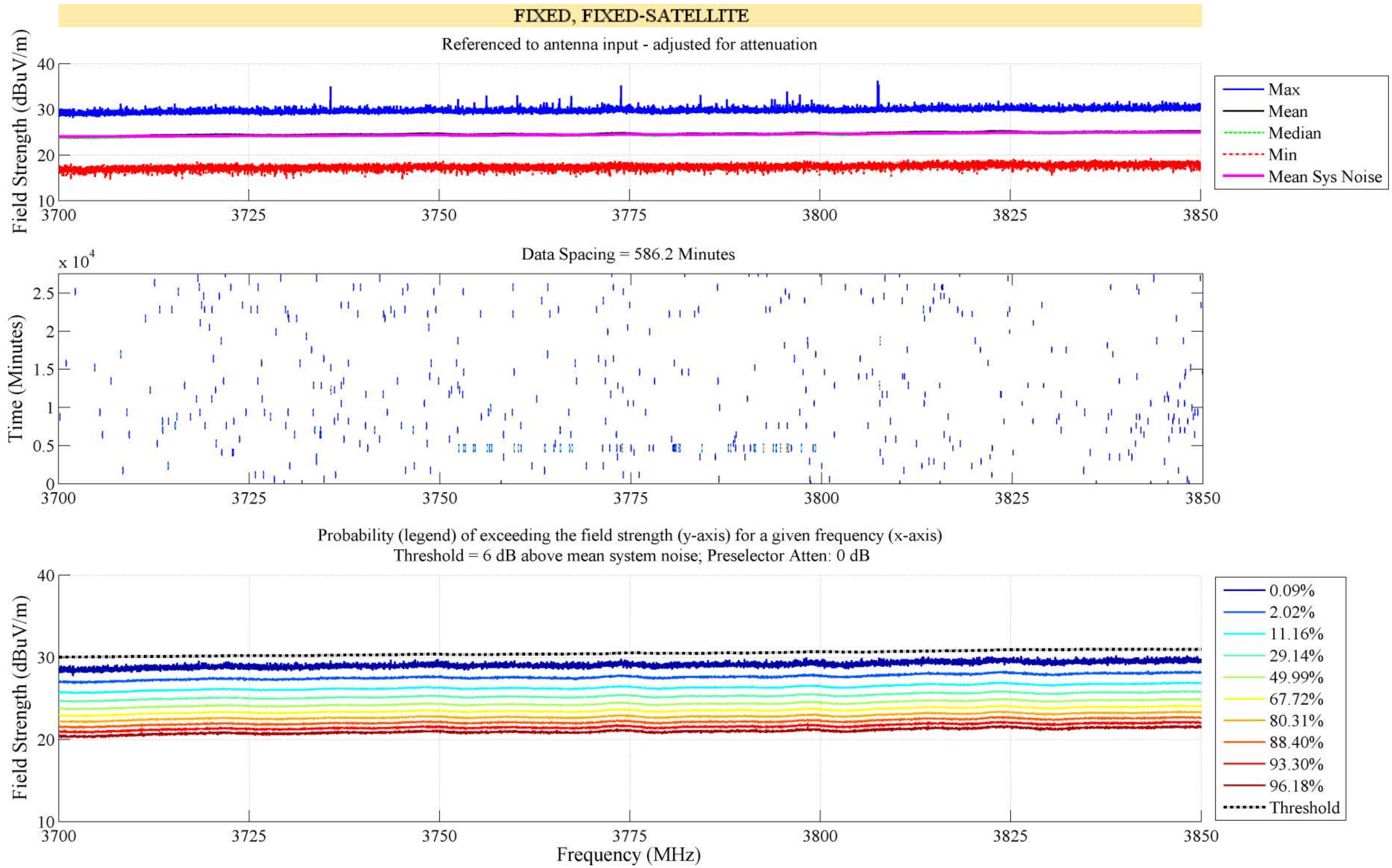

Figure 89. NTIA spectrum survey results from 3700 to 3850 MHz in Denver, CO, 2011.

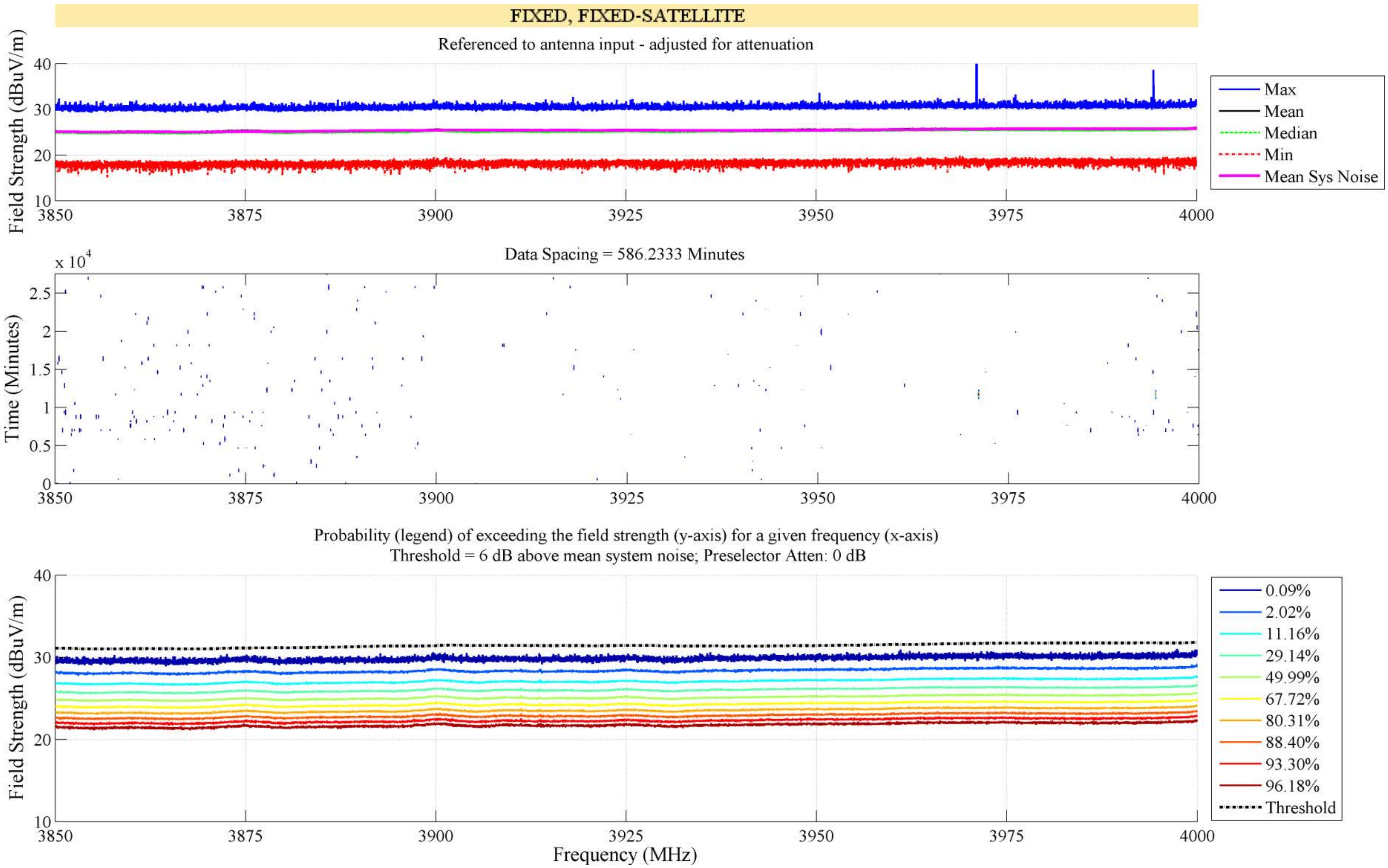

Figure 90. NTIA spectrum survey results from 3850 to 4000 MHz in Denver, CO, 2011.

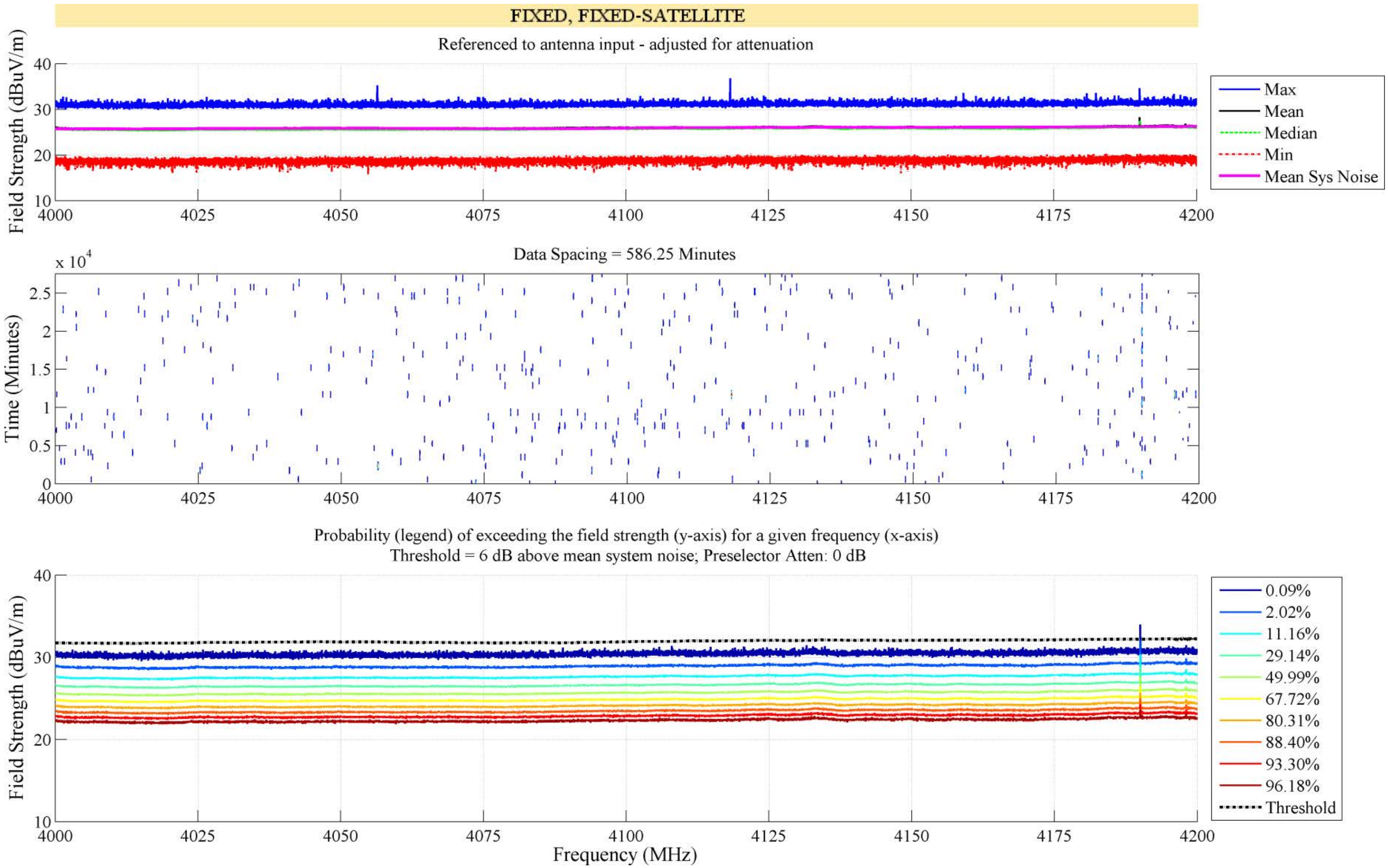

Figure 91. NTIA spectrum survey results from 4000 to 4200 MHz in Denver, CO, 2011.

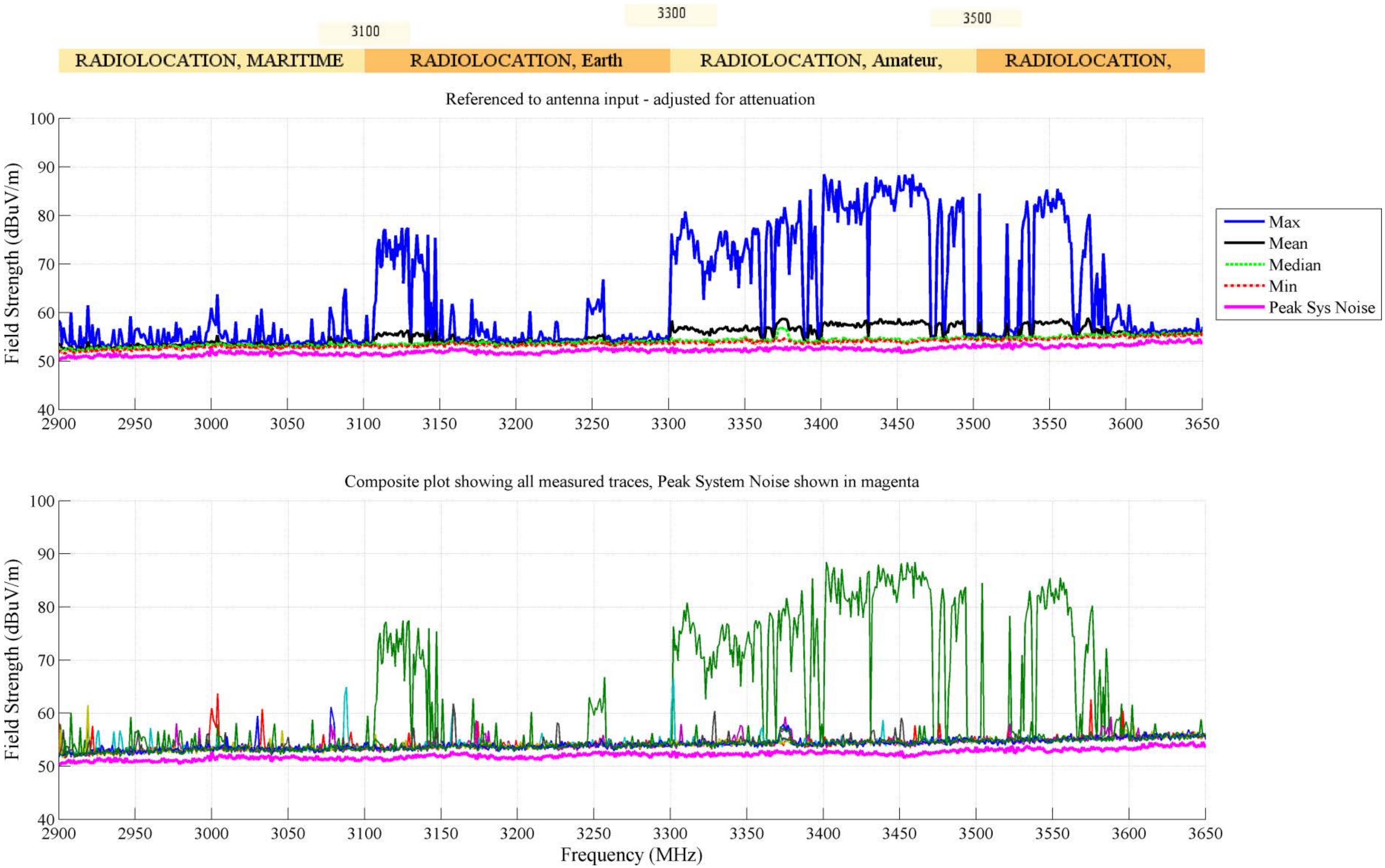

Figure 92. NTIA spectrum survey results from 2900 to 3650 MHz in Denver, CO, 2011. This measurement was taken using the stepped-spectrum measurement algorithm.

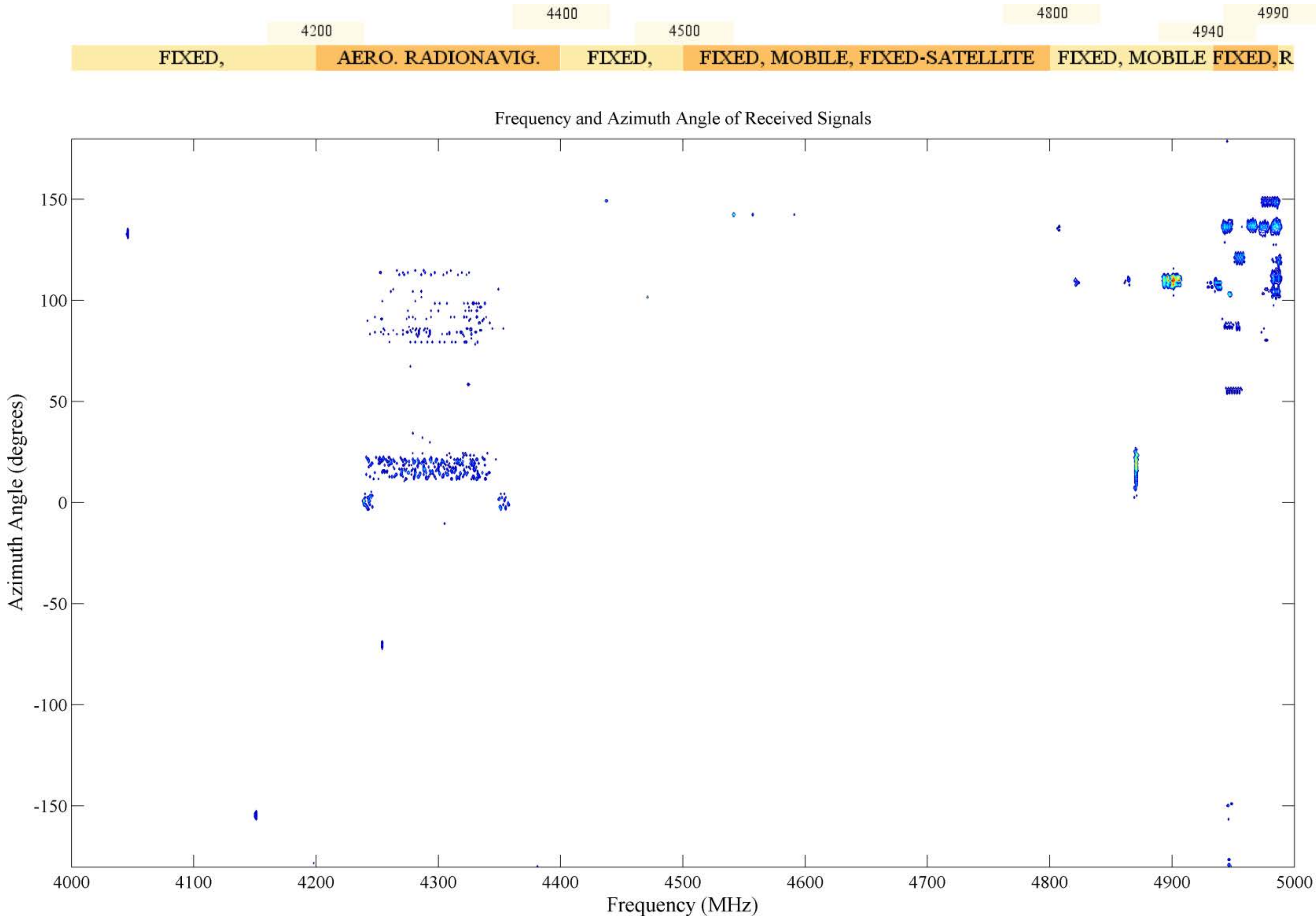

Figure 93. NTIA spectrum survey results from 4000 to 5000 MHz in Denver, CO, 2011. This measurement was taken using the azimuth-scanning measurement algorithm.

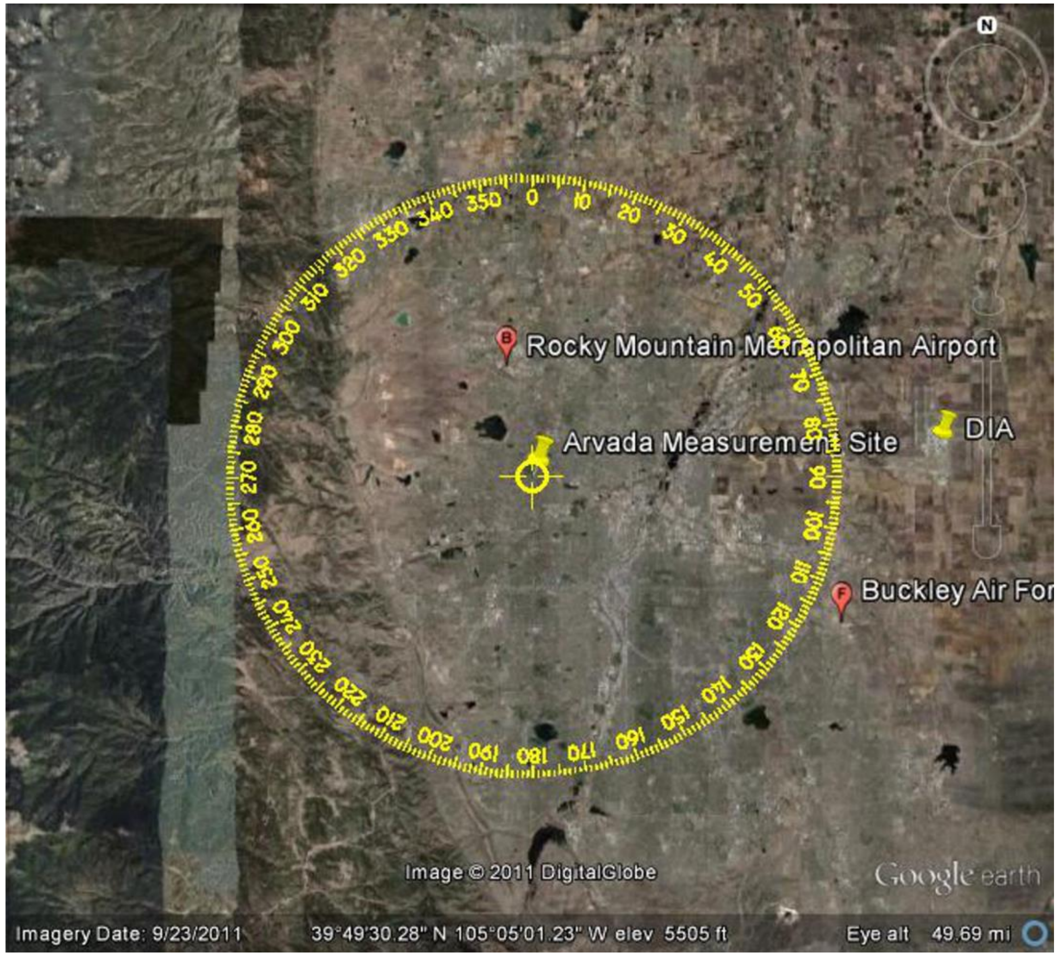

Figure 94. Compass centered on Arvada measurement location. The compass shows true north. Zero degrees on the plot is magnetic north. Proximity of Rocky Mountain Metropolitan Airport, DIA, and Buckley Air Force Base are shown.

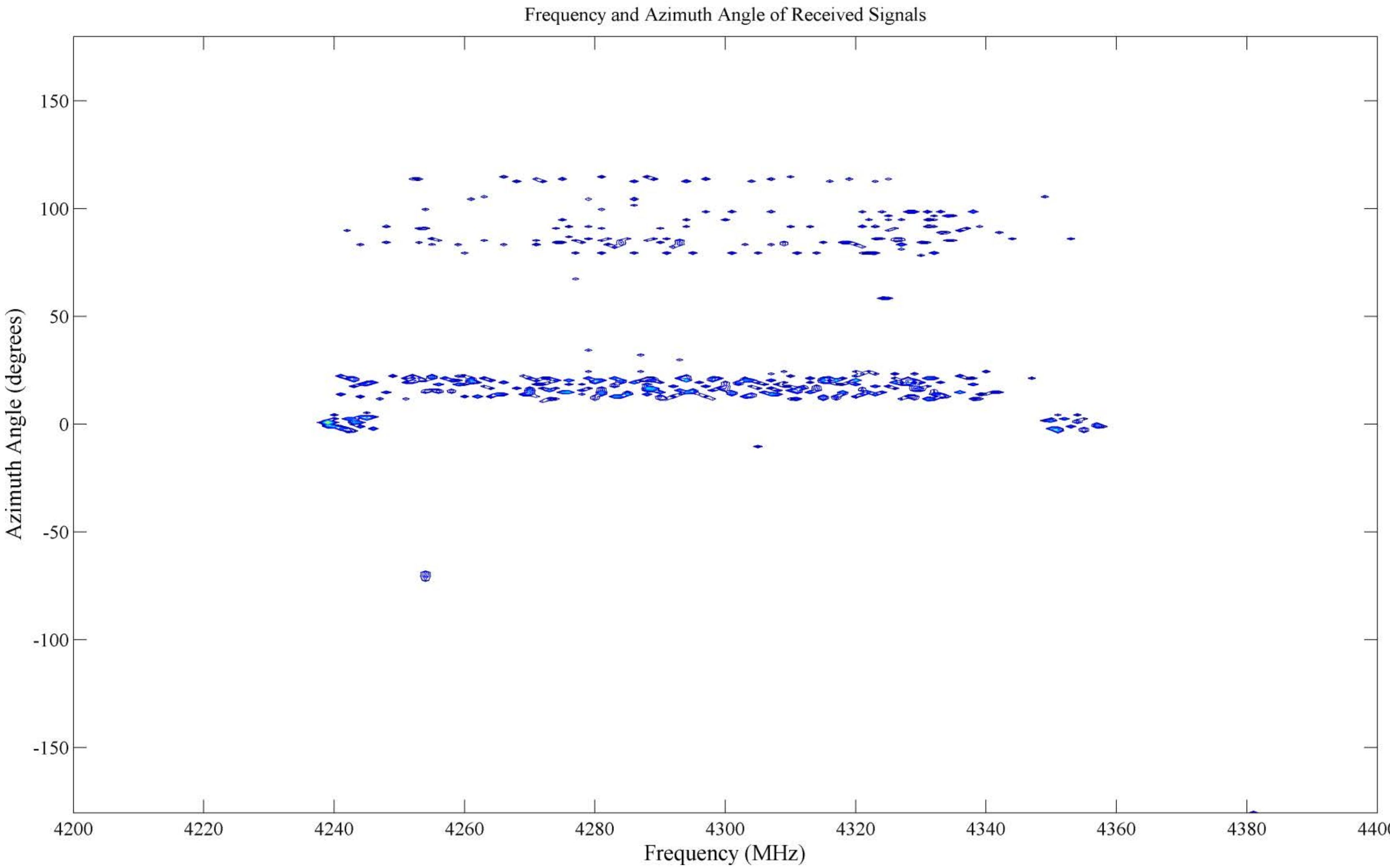

Figure 95. This graph is a close-up view of Figure 92, showing radio altimeter signatures.

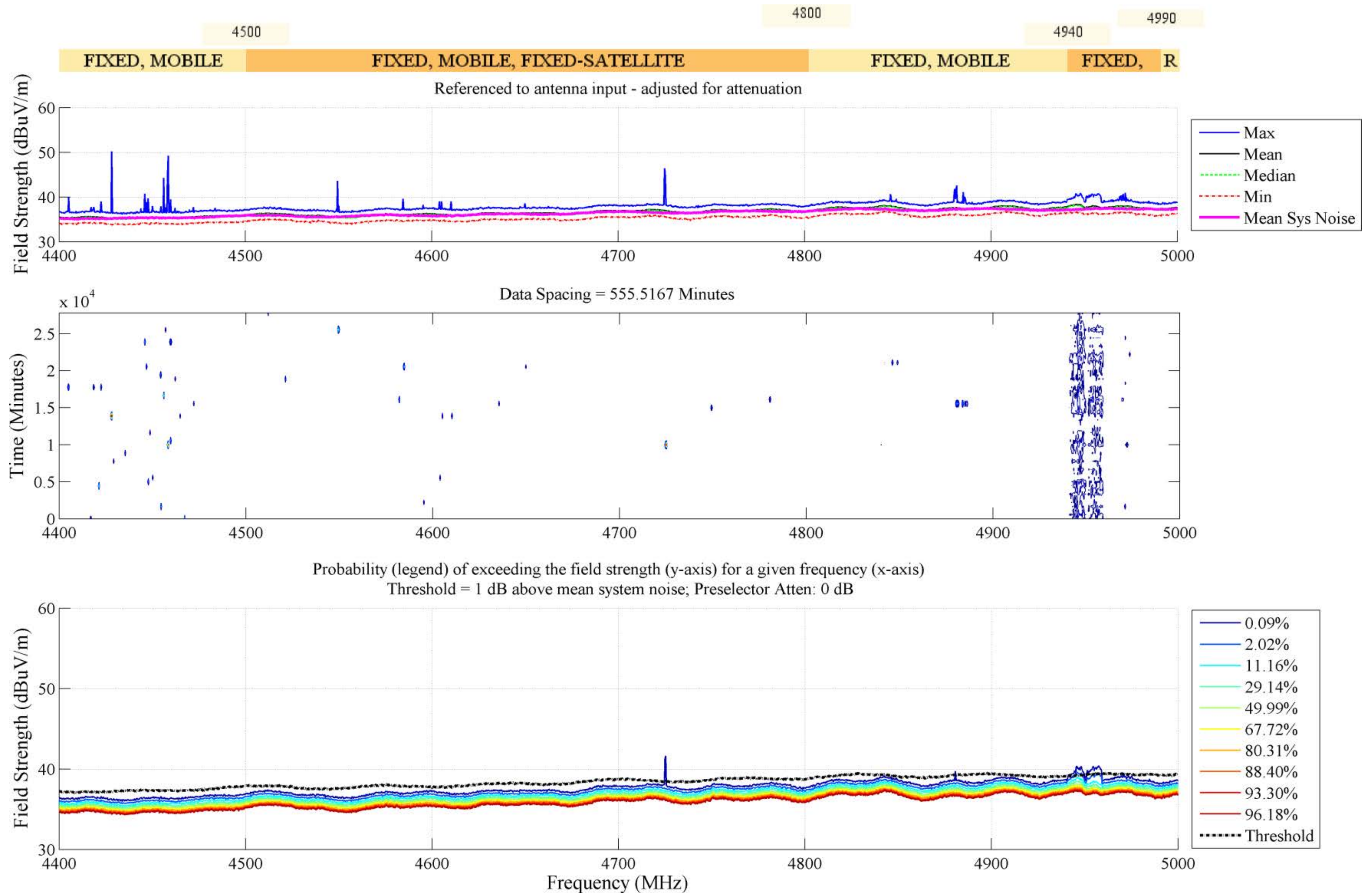

Figure 96. NTIA spectrum survey results from 4400 to 5000 MHz in Denver, CO, 2011. This measurement was taken using the swept-spectrum measurement algorithm.

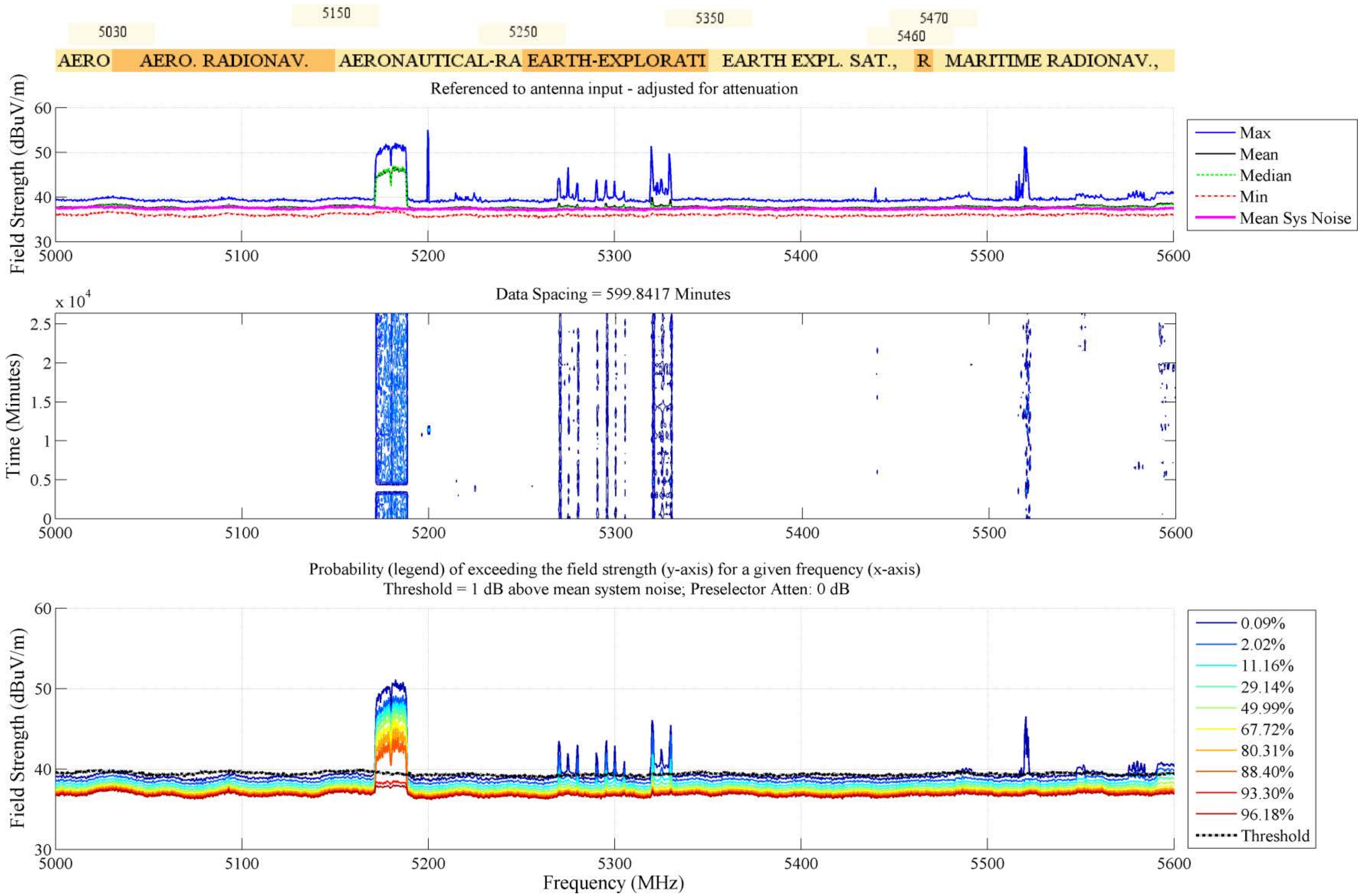

Figure 97. NTIA spectrum survey results from 5000 to 5600 MHz in Denver, CO, 2011. This measurement was taken using the swept-spectrum measurement algorithm.

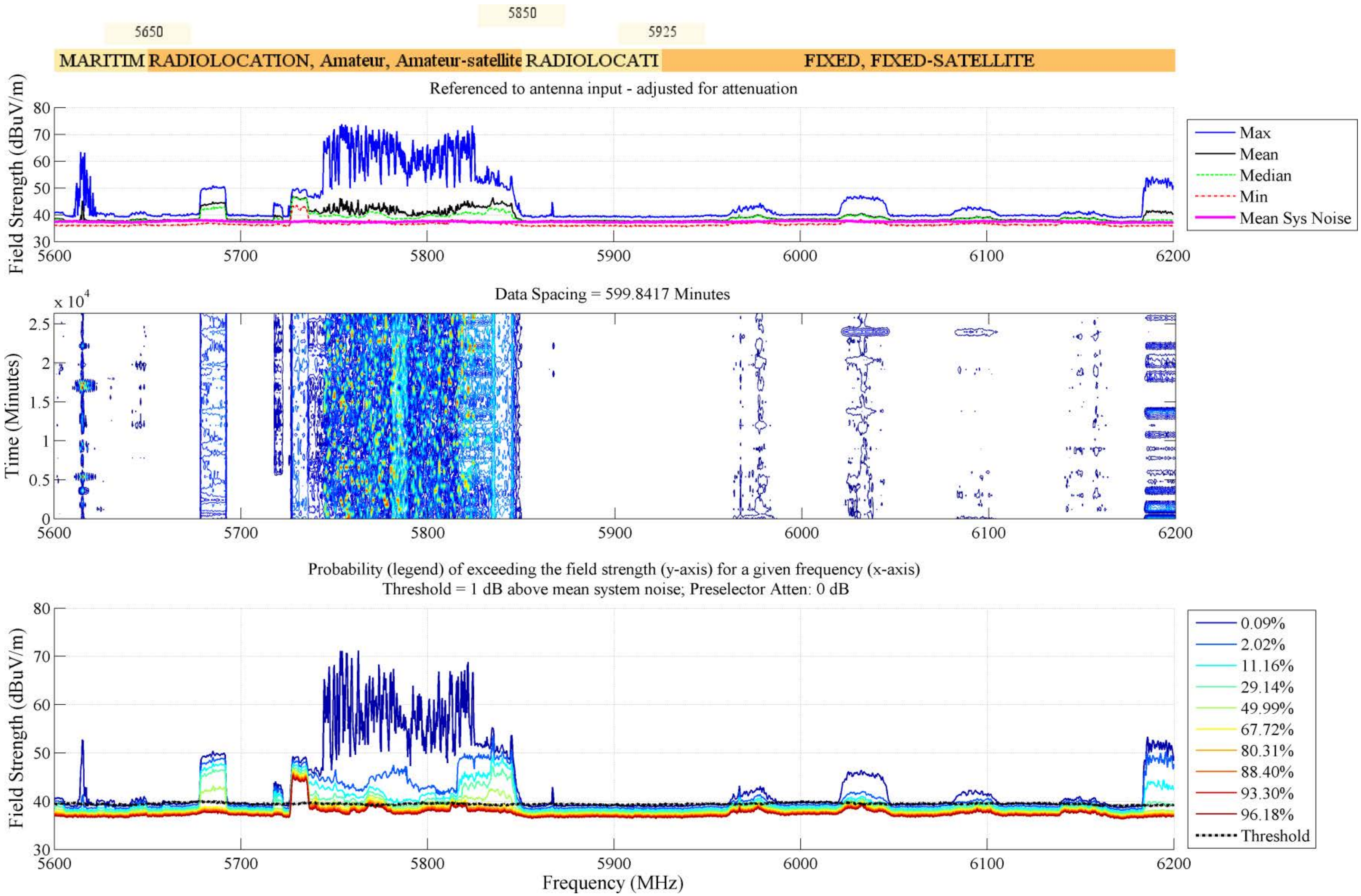

Figure 98. NTIA spectrum survey results from 5600 to 6200 MHz in Denver, CO, 2011. This measurement was taken using the swept-spectrum measurement algorithm.

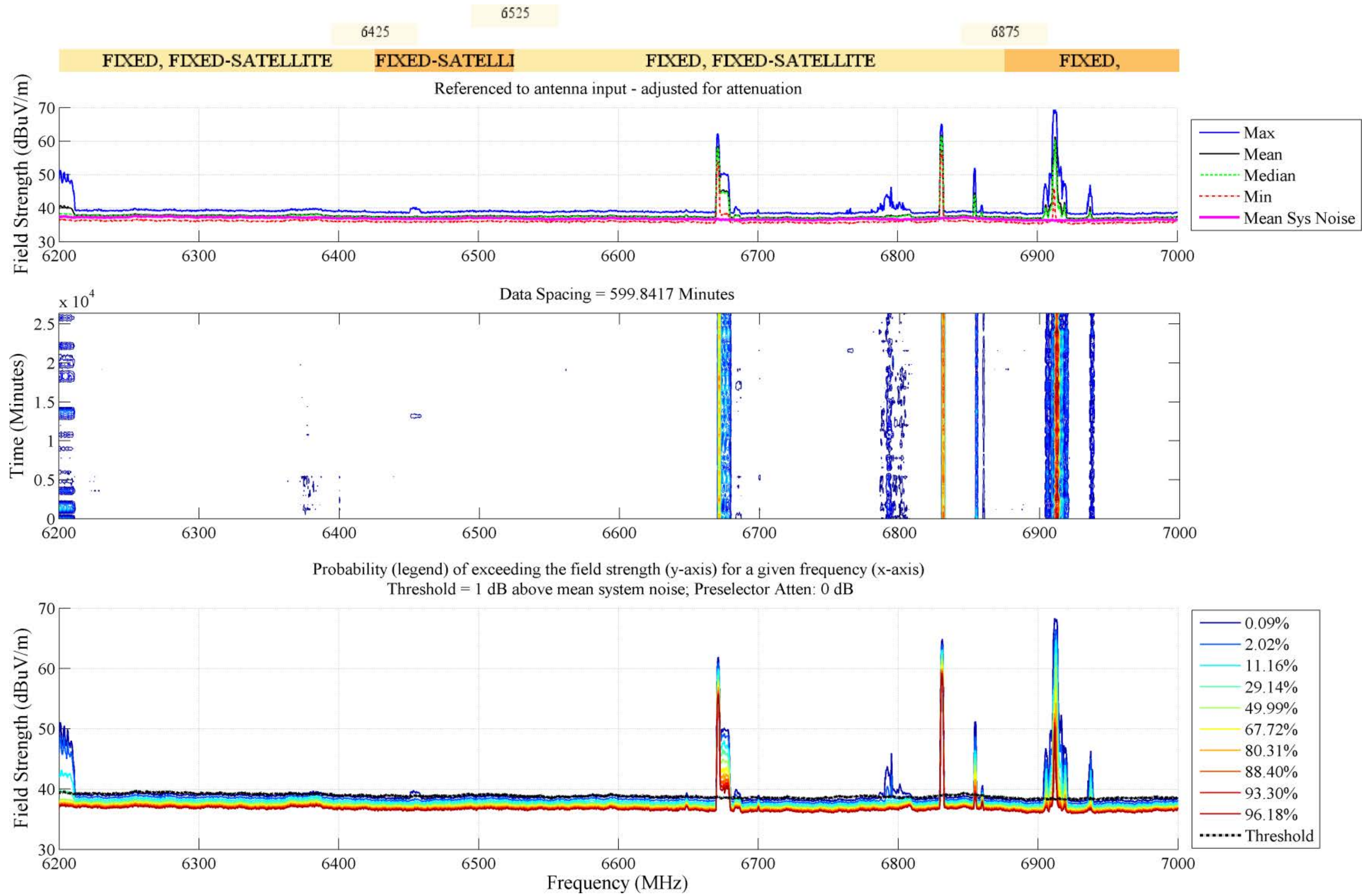

Figure 99. NTIA spectrum survey results from 6200 to 7000 MHz in Denver, CO, 2011. This measurement was taken using the swept-spectrum measurement algorithm.

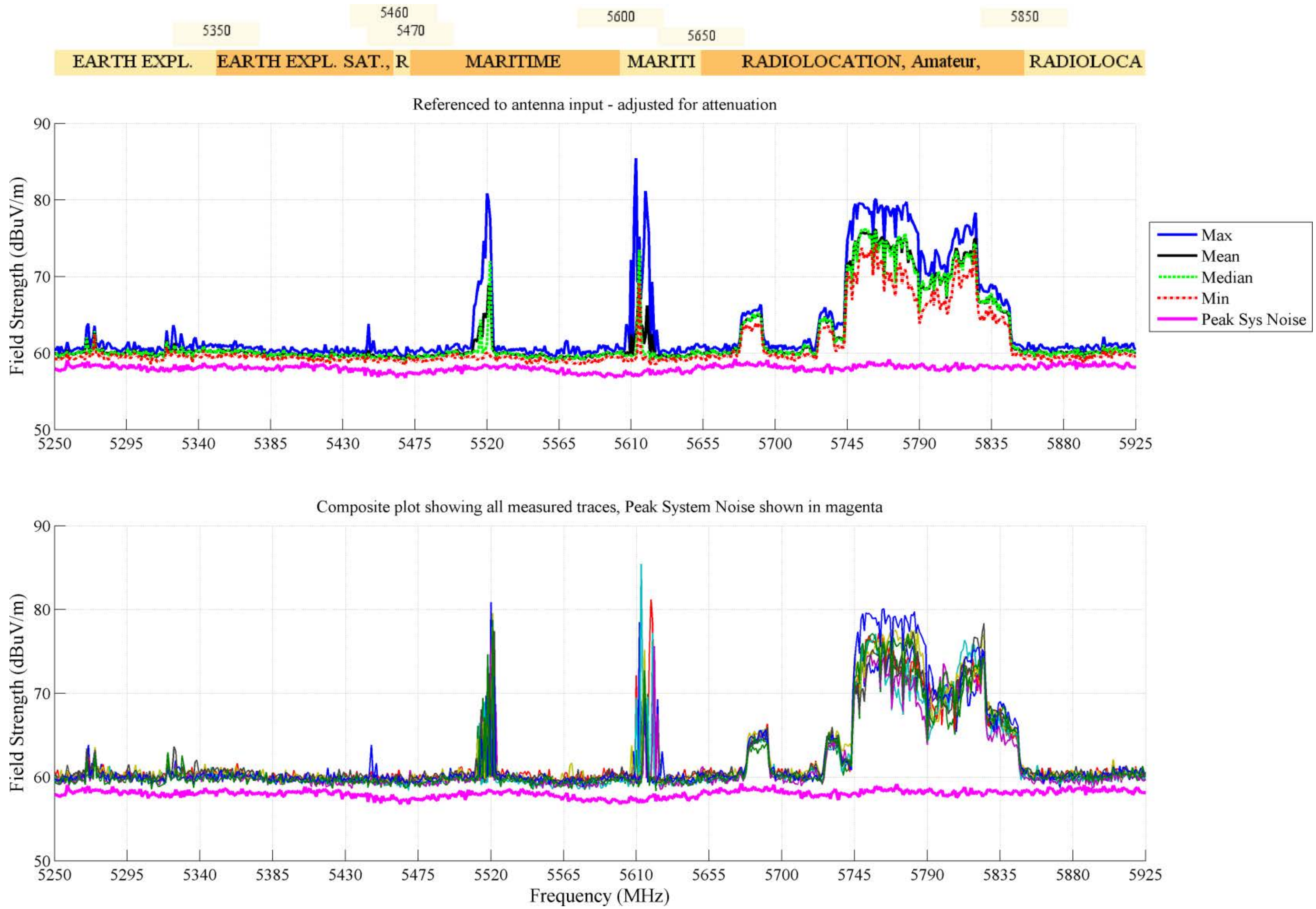

Figure 100. NTIA spectrum survey results from 5250 to 5925 MHz in Denver, CO, 2011. This measurement was taken using the stepped-spectrum measurement algorithm.

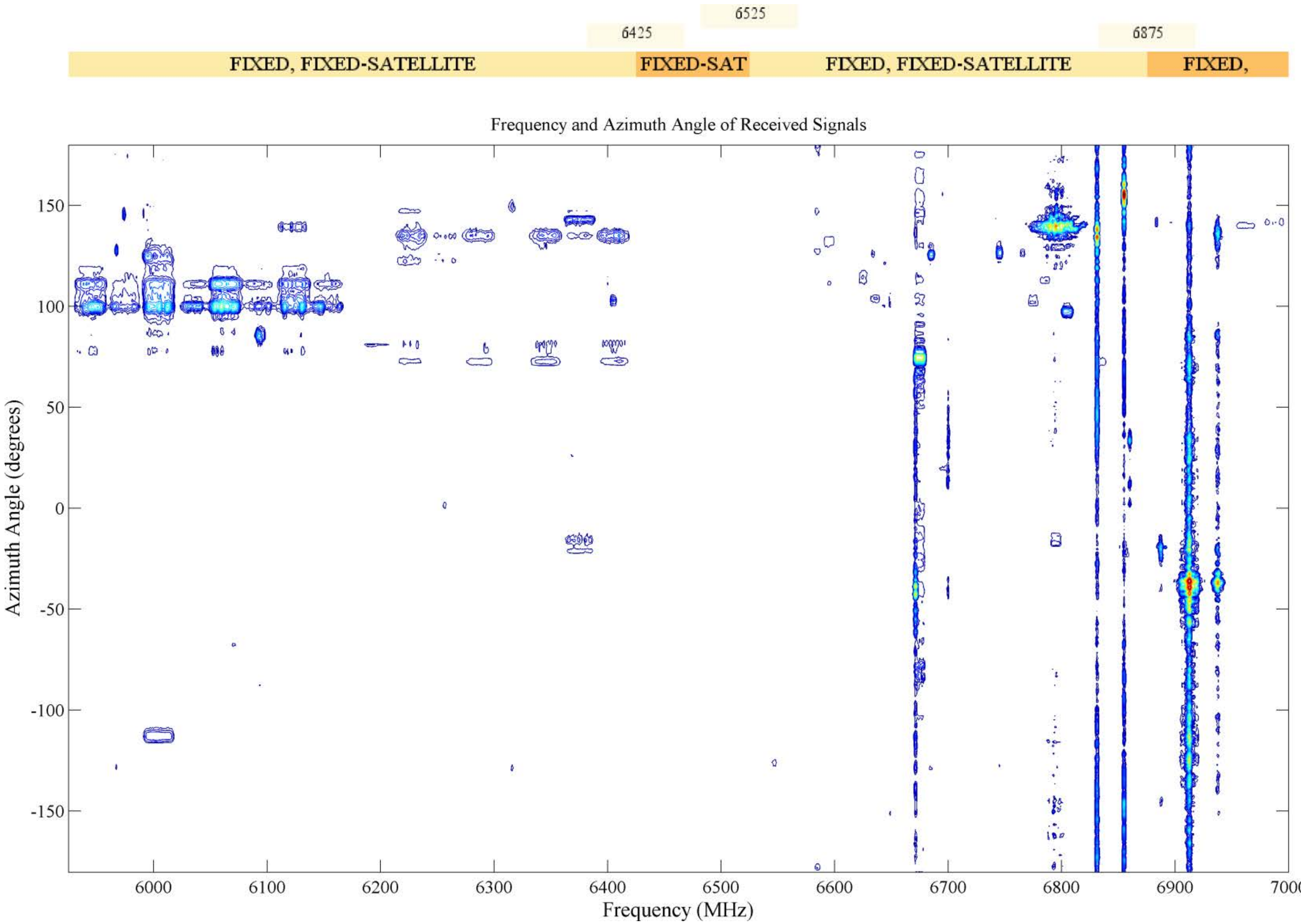

Figure 101. NTIA spectrum survey results from 5925 to 7000 MHz in Denver, CO, 2011. This measurement was taken using the azimuth-scanning measurement algorithm.

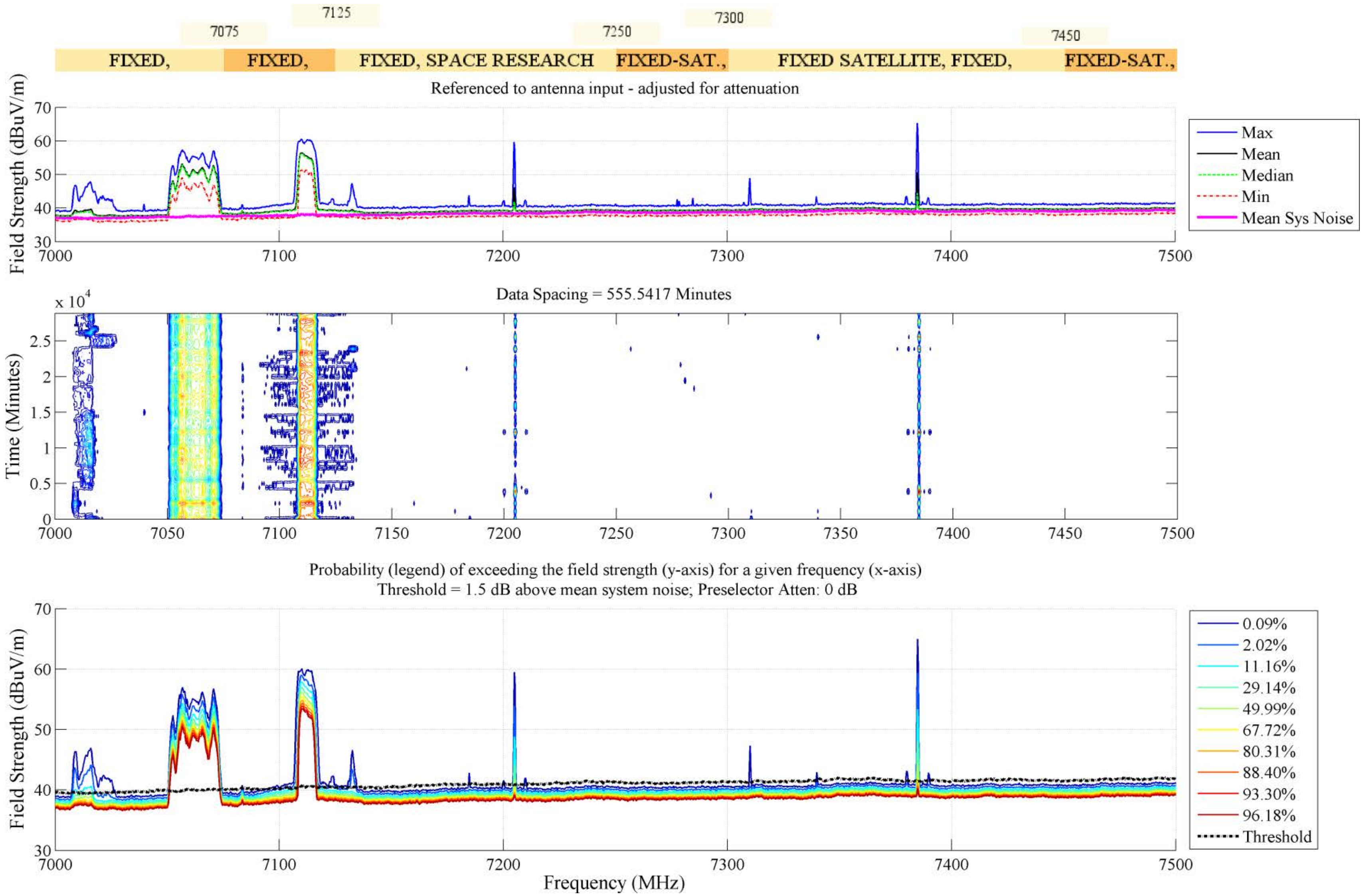

Figure 102. NTIA spectrum survey results from 7000 to 7500 MHz in Denver, CO, 2011. This measurement was taken using the swept-spectrum measurement algorithm.

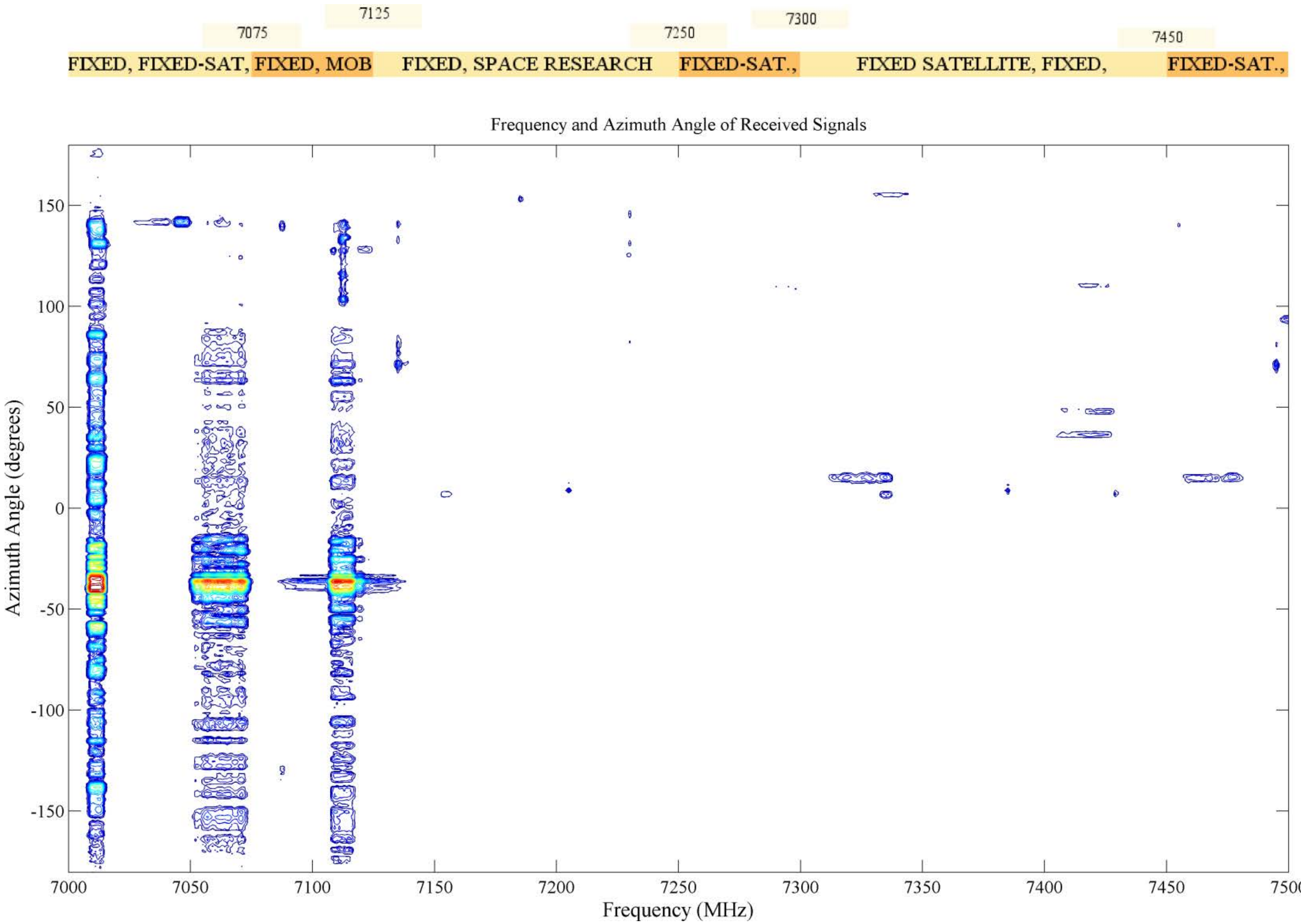

Figure 103. NTIA spectrum survey results from 7000 to 7500 MHz in Denver, CO, 2011. This measurement was taken using the azimuth-scanning measurement algorithm.

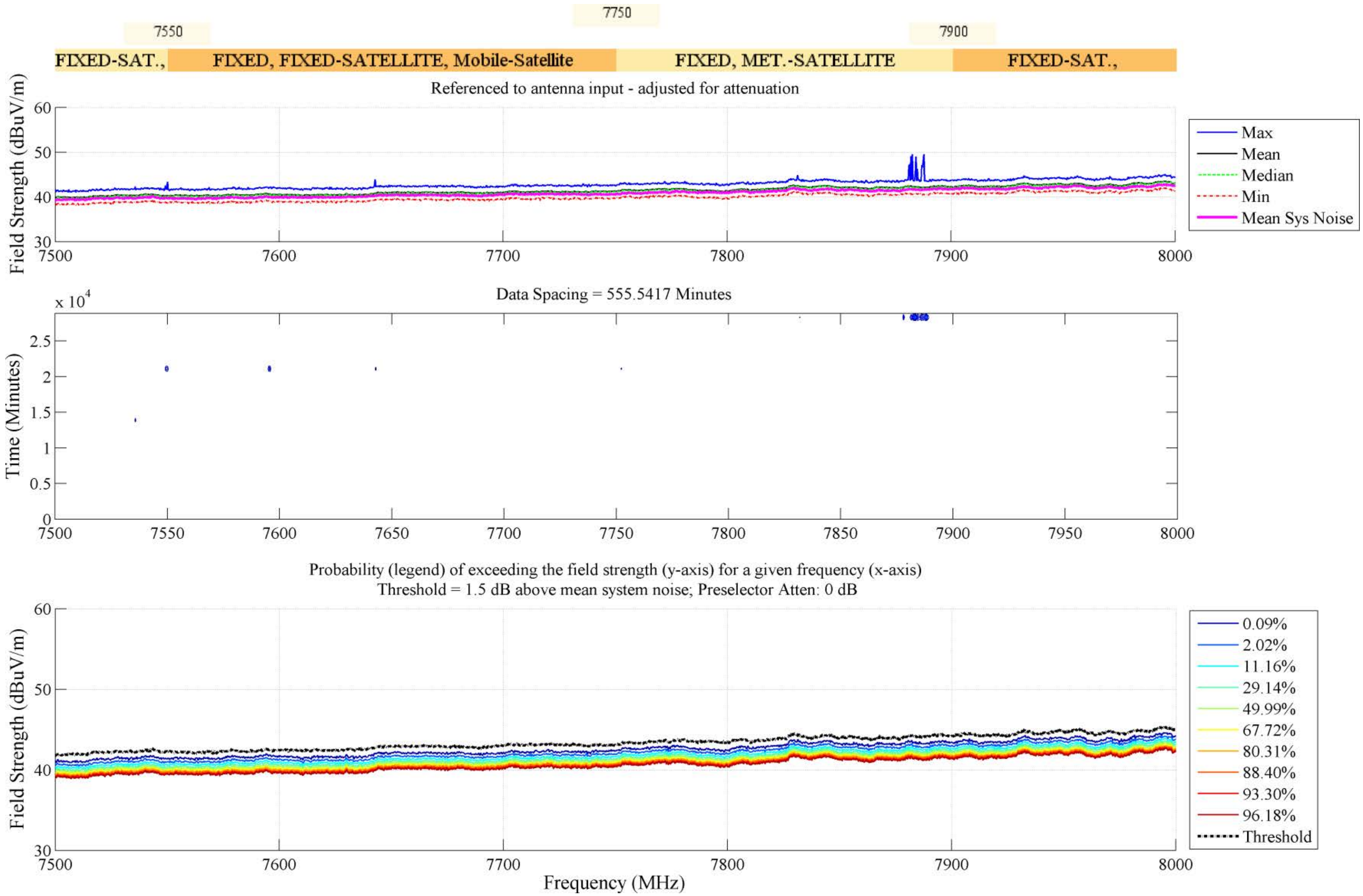

Figure 104. NTIA spectrum survey results from 7500 to 8000 MHz in Denver, CO, 2011. This measurement was taken using the swept-spectrum measurement algorithm.

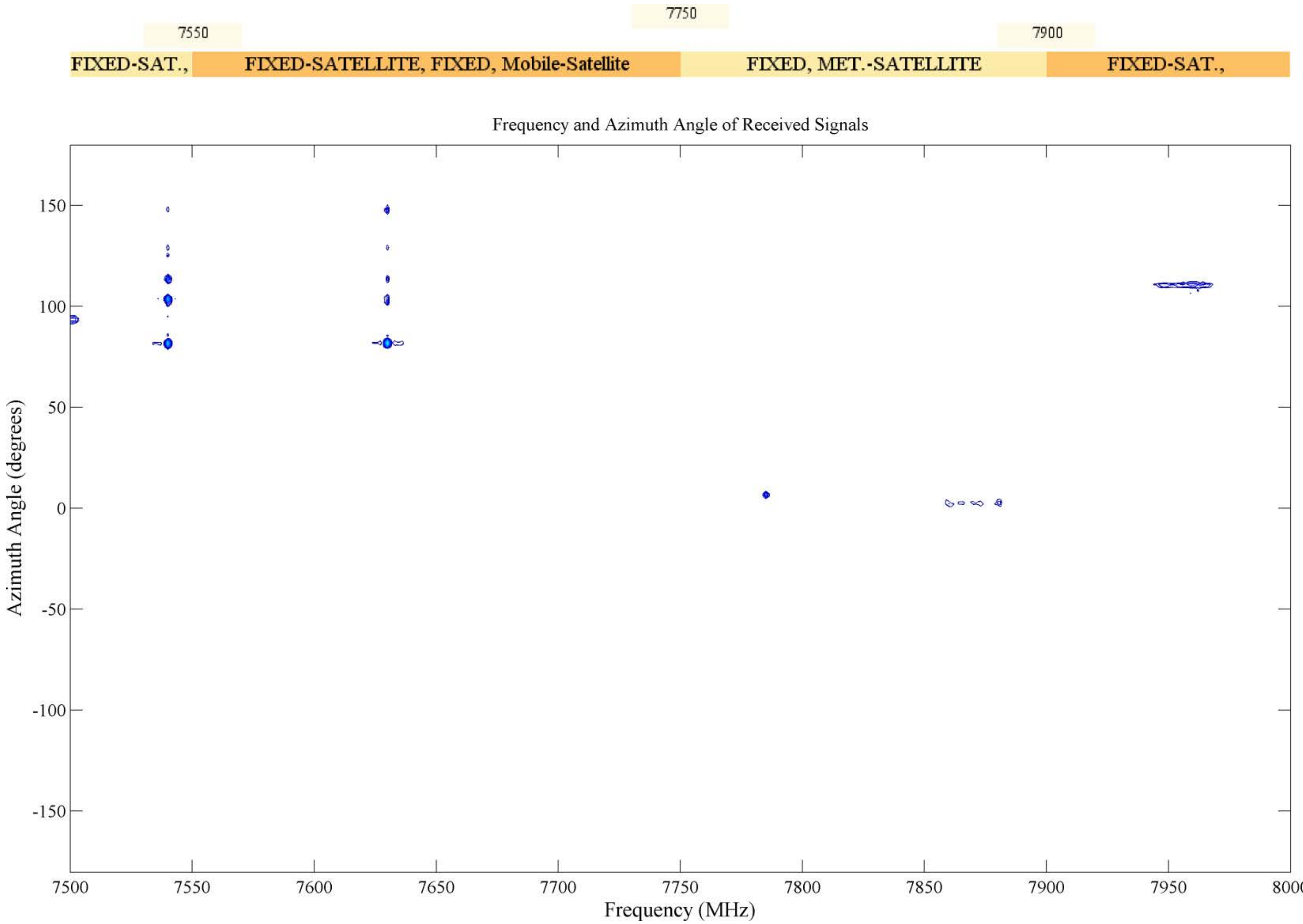

Figure 105. NTIA spectrum survey results from 7500 to 8000 MHz in Denver, CO, 2011. This measurement was taken using the azimuth-scanning measurement algorithm.

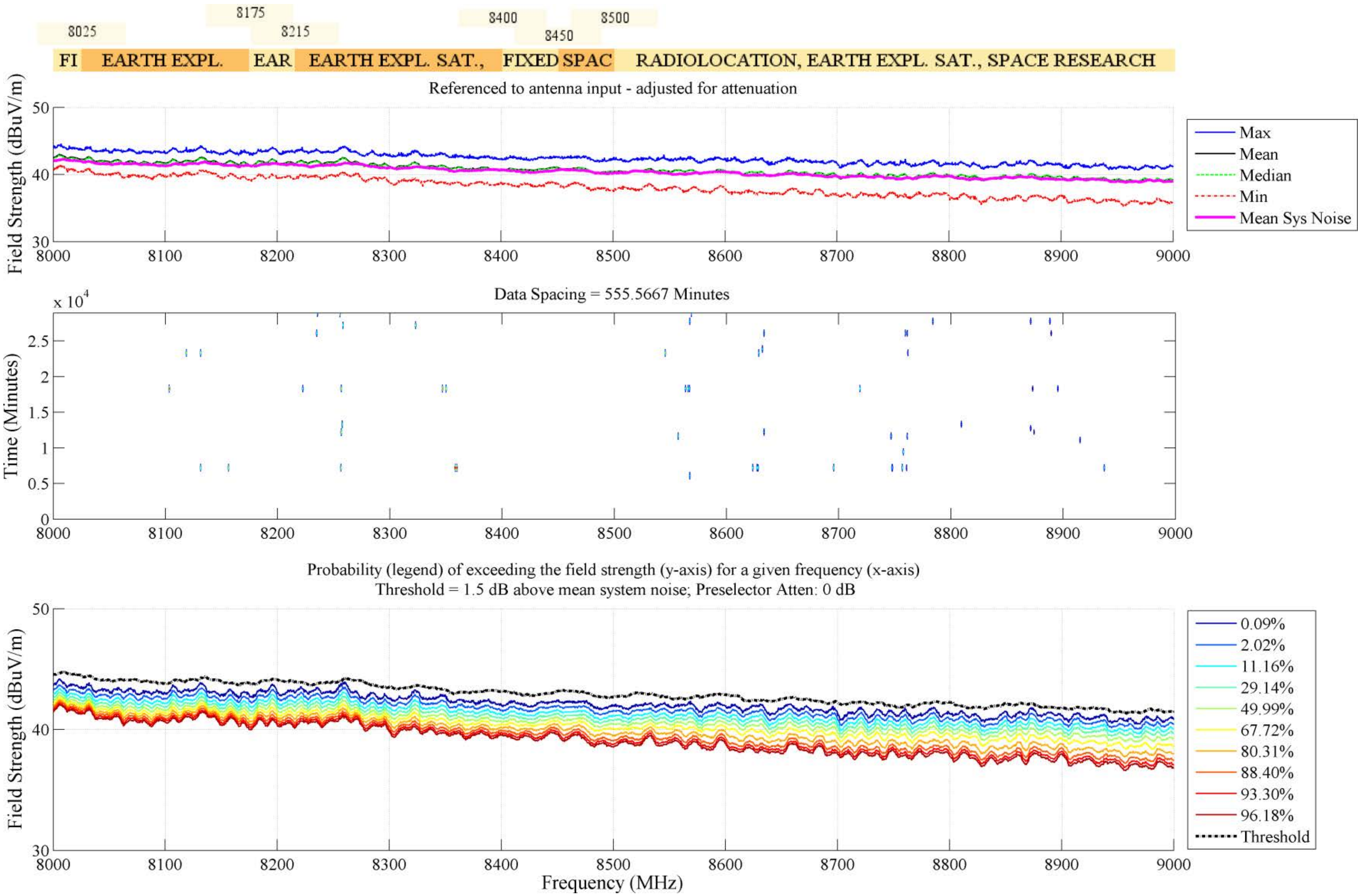

Figure 106. NTIA spectrum survey results from 8000 to 9000 MHz in Denver, CO, 2011. This measurement was taken using the swept-spectrum measurement algorithm.

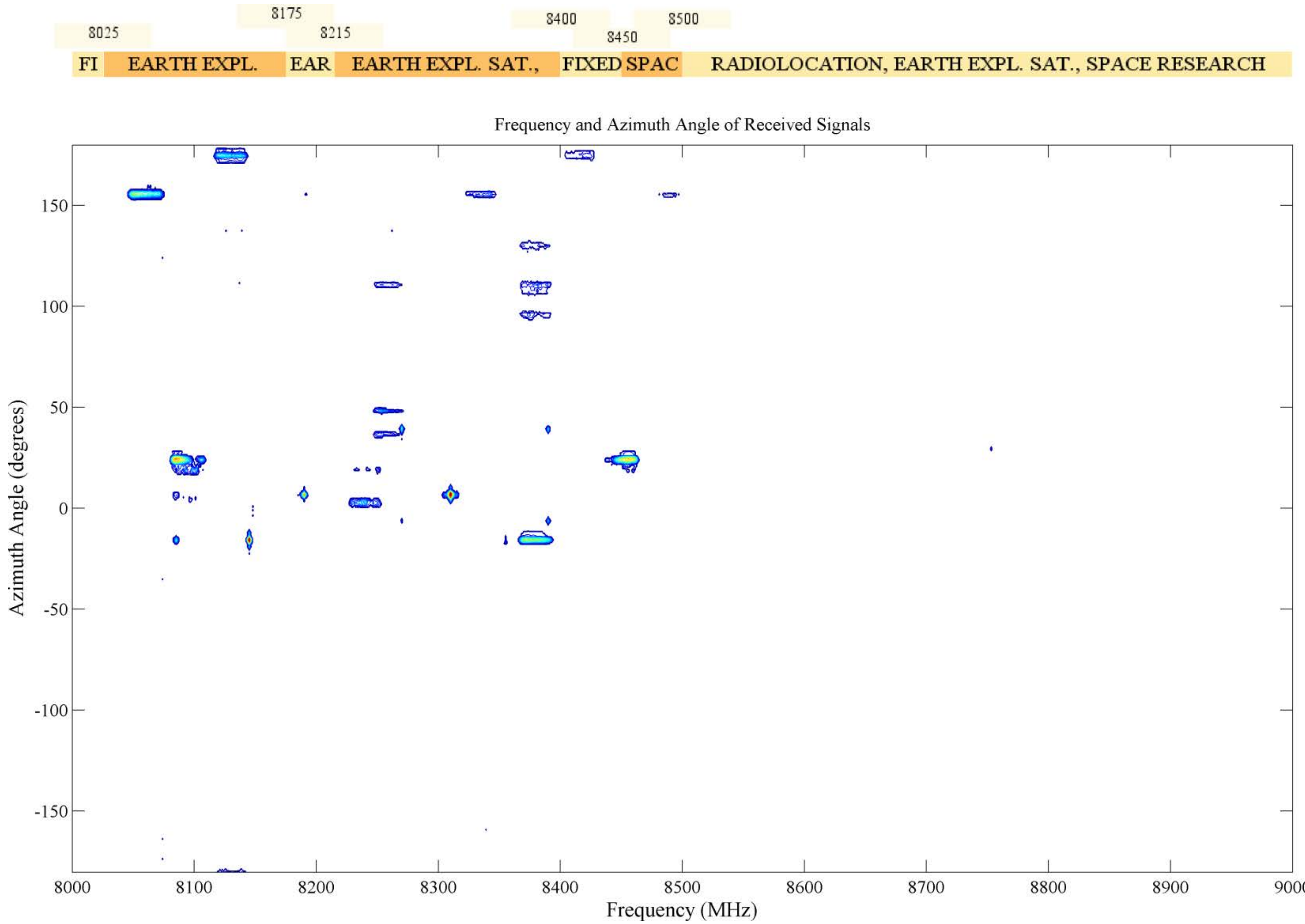

Figure 107. NTIA spectrum survey results from 8000 to 9000 MHz in Denver, CO, 2011. This measurement was taken using the azimuth-scanning measurement algorithm.

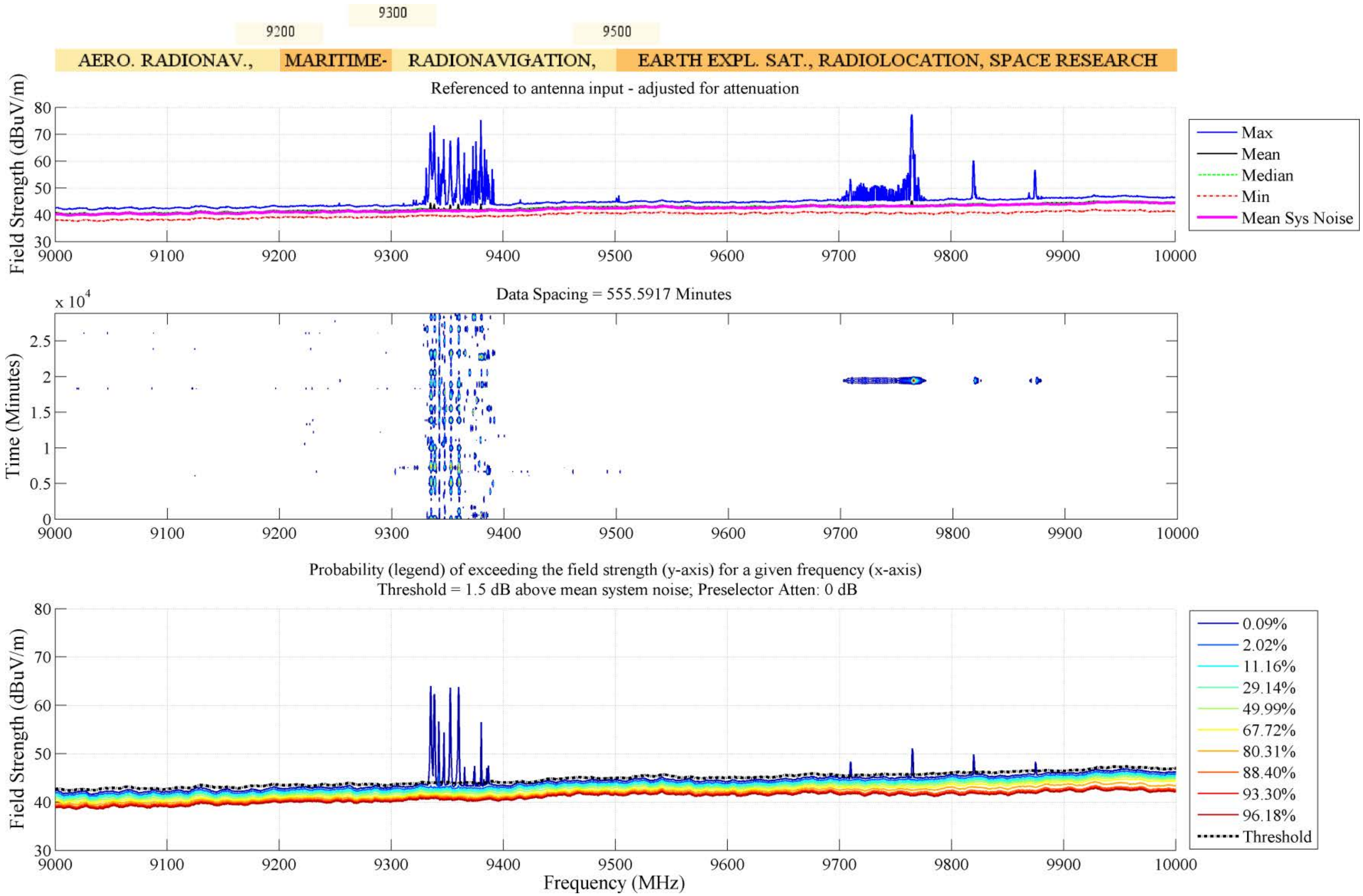

Figure 108. NTIA spectrum survey results from 9000 to 10000 MHz in Denver, CO, 2011. This measurement was taken using the swept-spectrum measurement algorithm.

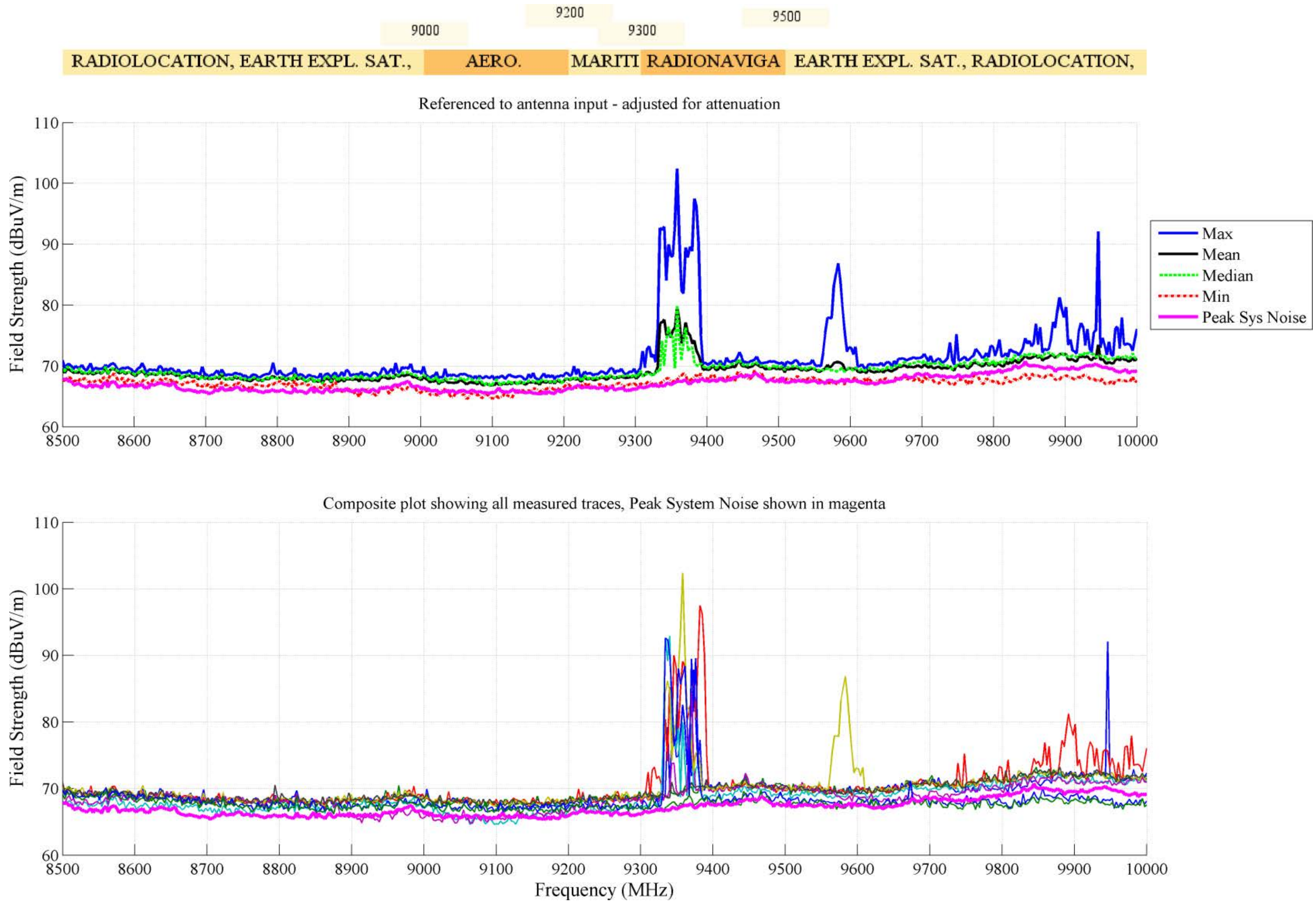

Figure 109. NTIA spectrum survey results from 8500 to 10000 MHz in Denver, CO, 2011. This measurement was taken using the stepped-spectrum measurement algorithm.

3.1 Discussion of Measured Data

A discussion of Figures 3–6 is provided to give the reader an understanding of how to interpret the data contained in the graphs. After this brief introduction, Table 4 provides notes about specific measurement results presented in the figures. For a more complete understanding of the frequency allocations in each measured band, the reader is directed to references [1], [8], [10], and [11].

Figure 3 shows a signal from 108.0 to 108.1 MHz that exceeds a field-strength level of approximately 37 dBμV/m with a probability of 96.18%. We also see that the signal has a 0.09% probability of exceeding approximately 57 dBμV/m. The waterfall plot shows this signal is on continuously. The waterfall plot also shows the presence of impulsive noise as evidenced by the horizontal striping in the data. Time data is plotted every 16.45 minutes for a total time of approximately 30,000 minutes, 500 hours, or 21 days. There is another signal at approximately 111.7 MHz that exceeds a field-strength level of approximately 20 dBμV/m with a probability of 96.18% and the field-strength level of 33 dBμV/m with a probability of 0.09%. This signal was on intermittently for the entire time that data was taken. This particular signal corresponds to an assignment in the GMF database. Most of the activity in this band is suppressed due to the 30 dB of preselector attenuation that had to be added to overcome adjacent channel noise sources. An attenuator applied in the entire measurement band reduces sensitivity to low-power signals; therefore, future surveys may include a high-pass filter or attenuation to minimize out-of-band signals that leak into the band of interest. The mean system noise level is at approximately 22 dBμV/m and the threshold used to plot the time-information is 10 dB above the mean system noise level.

Figure 4 shows data from 112 to 116 MHz. There is a prominent signal at about 115.4 MHz that was on continuously during the survey. It exceeds a field-strength level of approximately 38 dBμV/m with a probability of 88.40%. There is another low-level signal at approximately 114.6 MHz that was on during the entire survey, as noted by its presence at the 96.18% level, but shows up in the waterfall plot only intermittently because it does not break above the threshold. We notice in regions where there is no signal, the FS-CCDF lines are spaced in field strength by approximately 1 dB which indicates the system noise is Gaussian distributed and was measured with the TDwFFT algorithm. The upper lines are more widely spaced due to the presence of impulsive noise. The mean system noise trace lies slightly below the mean and median data traces, which indicates that external noise sources such as impulsive noise or broadband emissions have contributed to the noise floor of the measurement system.

Figure 5 shows data taken from 116 MHz to 120 MHz. There are signals that exceed the 96.18% field strength level at 116.3 MHz, 117.9 MHz, 117.97 MHz, and several signals between 118.5 and 120 MHz. There is also a lot of impulsive noise in this band which exceeds a given field-strength level with a small probability. Some signals are on continuously and others appear intermittently.

Figure 6 shows data taken from 120 MHz to 124 MHz. There is a signal at approximately 121.25 MHz that exceeds a field-strength level of -5 dBμV/m with a probability of 67.72%. This is a low-power signal that appears infrequently in the middle of the graph because it exceeds the threshold level only 2.02% of the time.

Table 4. Notes on Figures 3–109.

Figure(s)	Frequency Range (MHz)	Notes
3-5	108.0–117.975	The aeronautical radionavigation signals in this band, which include aviation, VOR, and Differential Global-Positioning System (DGPS), are generally low-level signals. This band is adjacent to the 88–108 MHz FM radio band which, in the Denver area, has a high-level signal at 107.9 MHz. To suppress the FM signal above 108 MHz, we inserted 30 dB of preselector attenuation into the 108–116 MHz frequency bands, which reduces the ability of our system to detect the low-level aeronautical radionavigation signals. Consequently, measurement results may understate Denver area usage in frequencies from 108 to 116 MHz .
5-8	117.975–136.0	The aeronautical mobile signals in this band originate from air traffic control (ATC), private aircraft, and search and rescue. These signals are characterized by their small bandwidth and are typically only detected for short periods, as can be seen in Figures 5–8.
9	136.0–137.0 137.0–138.0	The signals in these bands originate from aeronautical mobile, space operations and research (space-to-earth) transmissions. The FAA uses this band for ATC via the Automated Weather Observation System (AWOS) and the Automated Terminal Information System (ATIS). The National Aeronautics and Space Administration (NASA) uses this band for tracking and telemetry and the National Oceanic and Atmospheric Administration (NOAA) uses the band to collect meteorological data from the Geosynchronous Operational Environment Satellite (GOES). The Denver area survey shows low-level transmissions in this band.
10, 11	138.0–144.0	This band is generally used for non-tactical, trunked military land mobile communications and civil air patrol. We see several signals between 138.0 and 139.5 MHz and between 143.0 and 144.0 MHz. There is a single strong signal at approximately 141.4 MHz but with a received field strength of only around 40 dBµV/m.
11	144.0–148.0	The signals in this band are from amateur radio and amateur satellite. There are no Federal uses between 144.0–146.0 MHz. Most of the signals in this figure show moderate field strengths; however, they are typically on for very short periods of time.
11-14	148.0–162.0	These frequency bands are used by NASA for satellite uplinks and infrastructure functions. Other fixed or mobile signals for Civil Air Patrol, military non-tactical mobile, fixed communications, transit-satellite downlinks, land transportation, public safety, industrial, Earth telecommand, VHF distress systems communication, and industrial are found in this band. Maritime-mobile signals would be found at 156.2475–157.1875 MHz and 161.575–162.0125 MHz, but are not seen in the Denver area.
14-16	162.0–174.0	Fixed and mobile transmitters such as LMR and weather radio, used by public safety and industry, are found throughout this band. The signal at 162.55 MHz is a public broadcast weather information channel. The signal activity around 164.5 MHz could be a modulated signal, an emission that frequency hops, or multiple signals turning on and off.

Figure(s)	Frequency Range (MHz)	Notes
17, 18	174.0–216.0	This part of the spectrum is used for broadcasting television. Channels 7, 9, 11, and 13 are occupied with Advanced Television Systems Committee (ATSC) transmissions. There are signals in the white spaces between these channels which could be from subscription TV services or limited wireless microphones. There are no Federal uses in this band.
19	216.0–220.0	The signals in this band are from fixed, mobile, radiolocation and amateur transmitters. The users in this band are automated maritime telecommunications systems, radiolocation, and non-Government telemetry, tracking and command (TTC). There are several experimental research allocations in this range. There is little activity in this band from approximately 216.5–218 MHz and again from 218.6–219.7 MHz. The signal at approximately 218.6 MHz appeared during the 3rd day and remained present through the end of the spectrum survey.
19, 20	220.0–225.0	Fixed and land mobile signals are found from 220.0 to 222.0 MHz and amateur signals from 222.0 to 225.0 MHz. The general uses in these bands are trunked and conventional LMR systems and amateur (1.25m band) radio. The four signals observed from 224.5 to 225.0 MHz have an impact on the mean curve.
21-34	225.0–328.6	This band is used for military tactical and training communications including ATC, space operations from 267 to 273 MHz, space-to-earth and earth-to-space communications, and mobile-satellite from 312 to 315 MHz. The National Science Foundation (NSF) uses this band for radio astronomy research from 322 to 328.6 MHz. There are no FCC assignments in these bands. These figures show low usage.
34	328.6–335.4	The only allocated signals in this band are for aeronautical radionavigation transmissions. Instrument landing systems are used by the Federal Aviation Administration (FAA) and DGPS and microwave scanning beam landing systems are used by NASA. Some of these assignments are paired with frequencies from 108 to 117 MHz and frequencies from 960 to 1215 MHz for VORs and TACANs. We see both intermittent signals and signals that are on continuously. We do not see a lot of spectrum use in this band.
34-40	335.4–399.9	This band is used by the military, North American Treaty Organization (NATO), U.S. Coast Guard, FAA and NASA for radio and airborne communications; the military uses frequencies from 380 to 399.9 MHz for trunked LMR. We see both intermittent signals and signals that are on continuously. We do not see a lot of spectrum use in this frequency band.
40	399.9–400.05 400.05–400.15 400.15–406.0	In this figure, it is not possible to read the primary allocation for two narrow bandwidths, 399.9–400.05 MHz and 400.05–400.15 MHz. The allocation for 399.9–400.05 MHz is "RADIONAVIGATION-SATELLITE, MOBILE-SATELLITE." We saw a continuous 400 MHz signal in Denver. The allocation for 400.05–400.15 MHz is the "STANDARD FREQUENCY AND TIME SIGNAL-SATELLITE" at 400.1 MHz ± 25 kHz. We saw one low-level signal in this band. Meteorological aids occupy the band 400.15–406.0 MHz and include NOAA and Department of Interior (DOI) radiosonde systems and satellite transmitter uplinks called data collection platforms (DCP). The military also uses this band for radio communication and MedRadio. We saw a number of signals that were on intermittently.

Figure(s)	Frequency Range (MHz)	Notes
41-43	406–406.1 406.1–420.0	The primary allocation in the 406–406.1 band is “MOBILE-SATELLITE,” which cannot be read from the graph. This band is used by Emergency Position-Indicating Radio Beacon (EPIRB), the Emergency Locator Transmitter (ELT) systems and for distress alert and locations using Search and Rescue Satellite Aided Tracking (SARSAT) to public safety rescue authorities. We did not see any signals in this band in this survey. The signals in the 406.1–420.0 band are from fixed, land-mobile, radio astronomy, and space research signals. Federal agencies use these bands for trunked LMR and transmission of hydrologic and meteorological data. The NSF uses this for radio astronomy and NASA used this for remote operation of cranes and extra-vehicular activity (EVA) communications. There are LMR control channels from 406.1 to 411 MHz. There appears to be some type of impulsive noise source generated from approximately 419.25 to 420 MHz as shown by the horizontal “scratch marks” in the waterfall plot and from the raised maximum trace in the top graph.
44-46	420.0–450.0	The signals in this band originate from radiolocation and amateur radio. General uses in this band include private land mobile and amateur radio. Certain military and Federal agencies also use this band for long-range surveillance radars, enhanced position location reporting systems (EPLRS), space telecommand (449–451 MHz), wind-profiler weather radars (449 MHz), and synthetic aperture radars (SARs) (432-438 MHz). This frequency range was measured using a stepped-spectrum measurement algorithm (Figure 45) to detect radar signals and a swept-spectrum measurement algorithm (Figures 44 and 46) to detect all other signals. The signal at approximately 434 MHz in Figure 44 is also seen in Figure 45.
46, 47	450.0–470.0	Most of the signals in this band originate from land-mobile and fixed communications by non-Federal users. The secondary allocation from 460 to 470 MHz is for Federal meteorological satellite users. General uses in these bands are remote pickup, low power auxiliary, private land mobile, and maritime. Federal agencies use this for LMR shared systems and mutual aid responses with public safety agencies, and testing and evaluation of programs. There are medical telemetry transmissions occupying this band and NASA uses some of these frequencies to support balloon experiments. There are also space-to-earth and personal radio communications. This part of the spectrum is heavily used as indicated by the number of signals that have 96.18% exceedance levels in the FS-CCDF plot in Figure 46.
47-49	470.0–512.0	These bands are used by fixed, land-mobile and broadcasting services. However, there is no land-mobile activity in the Denver area in this band. Uses in this band include public mobile, broadcast radio (Channels 14–19), low power television (LPTV), TV translator/booster, low power auxiliary, private and land mobile services. Federal agencies use this band for shared LMR systems and mutual aid responses with the public sector. During the measurement, Channel 16 (482.0 to 488.0 MHz) was originally on and then turned off.

Figure(s)	Frequency Range (MHz)	Notes
49-60	512.0–793.0	Broadcasting, land-mobile, radio astronomy, and mobile signals are assigned in this band. The radio astronomy allocation and land-mobile is found from 608 to 614 MHz. Broadcast radio Channels 21–36 occupy frequencies from 512 to 608 MHz. We see that Channels 27 and 36 are still in the old National Television Systems Committee (NTSC) transmission format. Channels 38 to 51 occupy the spectrum from 614 to 698 MHz. The other utilizations in these bands include LPTV, TV translator/booster, low power auxiliary, personal radio, and Federal agencies, who use this band for experimental testing and evaluation of programs. Radio astronomy research for observing pulsars, the sun, the planet Jupiter, the Milky Way galaxy, and observations of spectral lines are present. The Department of Veterans Affairs (DVA) uses this band for medical telemetry devices. From 746.0 to 756 MHz we see a digitally-modulated signal which is the Verizon Long Term Evolution (LTE) signal.
60-63	793.0–902.0	Most of the signals in these frequencies originate from fixed, mobile, aeronautical-mobile and land mobile transmissions with a small primary allocation for broadcasting from 805.0 to 806.0 MHz. These bands are used by Federal agencies for experimental research and systems shared by public safety and military agencies. Military agencies operate some radar systems in the 854.0–902.0 MHz frequency band. There are public safety mobile and control channels from 806 to 824 MHz, commercial cellular mobile channels from 824 to 849 MHz, public safety base station transmit frequencies from 851 to 869 MHz, and commercial cellular base station transmit frequencies from 869 to 894 MHz. These figures show heavy usage during our survey.
64, 65	902.0–928.0	Signal allocations in this band are primarily for radiolocation and secondarily for amateur radio. The general utilizations for this band are Navy Air & Search, surveillance radars on ships and carriers, tracking radars for aeronautical flight testing monitor positions of missiles, drones, manned aircraft, security for intruder detection, NOAA wind profiler system and this is also one of the ISM bands. This frequency range was measured using a stepped-spectrum measurement algorithm (Figure 65) to detect radar signals and a swept-spectrum measurement algorithm (Figure 64) to detect all other signals. The waterfall plot shows constant usage during this spectrum survey.
64, 66	928.0–960.0	Signals in this band are from fixed, land mobile, and broadcasting services. General uses in this band include public mobile, aural broadcast auxiliary, fixed microwave, low power auxiliary, public safety shared systems, low-capacity (voice) systems for Federal agencies, and personal communication systems (PCS). Military agencies operate some radars in the 935.0–941.0 MHz frequency band. These bands show heavy usage during our survey.
66-69	960.0–1215.0	These bands are allocated for aeronautical radionavigation and radionavigation satellite services and are used by TACAN, Distance Measuring Equipment (DME), Air Traffic Control Radar Beacon System (ATCRBS) & Mode-S at 1030 MHz and 1090 MHz, microwave landing systems (MLS), Traffic Alert and Collision Avoidance System (TCAS), Automatic Dependent Surveillance Broadcast (ADS-B) at 978 MHz, and Joint Tactical Information Distribution System (JTIDS). The GPS-L5 operates in this band at a frequency of 1176.45 MHz ± 12 MHz. There are space-to-earth and earth-to-space communications in this band as well. Some of these frequencies are paired with those in the 108.0–117.0 MHz band and the 328.0–335.4 MHz band. The frequency gap between Figures 66 and 67 is due to the unintentional omission of a band event from 962.0 to 971.0 MHz. Signal levels in the GPS L5 band (1164–1188 MHz) are as expected.

Figure(s)	Frequency Range (MHz)	Notes
69-71	1215.0–1400.0	These bands contain assignments for earth exploration satellites, radiolocation, radionavigation satellites, space research, aeronautical radionavigation, fixed, mobile, and land-mobile services. There is also a secondary allocation for radiolocation services from 1300.0 to 1350.0 MHz. The general utilizations in these bands are GPS-L2, which operates at 1227.6 MHz ± 12 MHz, Wide Area Augmentation System (WAAS), High-power long-range surveillance radars, FAA operated air-route surveillance radars (ARSR), balloons for drug interdiction, SARs, shipborne radars, radio astronomy research, remote sensing, fixed-mobile communication links, and GPS at 1381.05 MHz. Personal radio exists in the upper part of this band as well as medical telemetry devices, wireless communications and earth-to-space fixed satellite. This frequency range was measured using a stepped-spectrum measurement algorithm (Figure 71) to detect radar signals and a swept-spectrum measurement algorithm (Figures 69 and 70) to detect all other signals. We see radar emissions between 1230–1390 MHz in Figure 71. One of the individual traces shows that the radar was turning on at the time of this measurement. The same radar emission at approximately 1334 MHz is visible in Figure 70 in the swept-spectrum measurements. Notice that the actual peak power of the radar is not captured in the swept-spectrum measurement. Signal levels in the GPS L2 band (1215–1239 MHz) are as expected.
72, 73	1400.0–1427.0 1427.0–1535.0	The allocation from 1400.0 to 1427.0 is for earth exploration satellites, radio astronomy, space research applications. This band is a passive band which means that it is a receive-only band. We do not know the source of activity measured by our survey from 1400 to 1427 MHz. Services in the frequency range 1427.0–1535.0 MHz include fixed, land-mobile, mobile, and mobile satellite services. This band is used for medical telemetry and telecommand, fixed telemetry, private land mobile, personal radio, wireless communication, aeronautical telemetry, flight testing of manned/unmanned aircraft missiles and space vehicles, range safety, aircraft chases, and weather data. Frequencies from 1525 to 1535 MHz contain mobile-satellite signals. Most of the activity in this band occurred from approximately 5000 minutes to 15000 minutes, or from 3.5 days into the measurement to about 10.5 days into the measurement.
73, 74	1535.0–1710.0	The allocations in this band are for radionavigation, satellite, radio astronomy, space research, meteorological aids and fixed and mobile services. The general utilizations are space-to-earth, satellite communications, maritime, aviation, GPS-L1 (1575.42 MHz ±12 MHz) International Marine/Maritime Satellite (INMARSAT) (1626.5–1645.5 MHz), SARSAT, EPIRB and ELT for public safety rescue, WAAS, passive remote sensing and passive space research, Deep Space Network (DSN), earth-to-space communications, radiosondes, GOES, and Television Infrared Operational Satellite (TIROS)-N. In the GPS L1 1559–1610 MHz Radio Navigation Satellite Service (RNSS) band there is a relatively high signal at approximately 1562 MHz (Figure 73).
74, 75	1710.0–1850.0	This frequency range is allocated for fixed, mobile, and space-operations. This band is used exclusively by Federal agencies to operate point-to-point microwave, tactical radio relay communications systems, mobile subscriber equipment, precision-guided munitions (PGM), the Air Force Satellite Control Network (AFSCN) & Space-Ground Link System (SGLS), telemetry, and telecommand. We saw five signals that were on continuously within the 1755.0 to 1850.0 MHz band during our survey.

Figure(s)	Frequency Range (MHz)	Notes
75-77	1850.0–2025.0	The main allocation for these bands is fixed and mobile services, however, there is a small bandwidth from 2000 to 2020 MHz carved out for mobile satellite services; we measured small signal levels at four frequencies. The entire frequency band allocation is non-Federal and some of the general uses are Radio Frequency (RF) devices, personal communications, fixed microwave, and earth-to-space satellite communications. Cellular frequencies occupy the band from 1850 to 1910 MHz and from 1930 to 1990 MHz and show heavy usage.
77-79	2025.0–2300.0	Federal agencies use this frequency range for space operations, earth exploration satellites, fixed and mobile services, and space-research. The non-Federal allocations in the frequency range are fixed and mobile services, mobile-satellite, and space research. General uses include TV auxiliary broadcasting, cable TV relay, and local TV transmissions. There are research and weather satellite systems in this band such as the DSN and the Tracking and Data Relay Satellite System (TDRSS). The Western Area Power Administration (WAPA) also has assignments in this band. Non-Federal allocations include public mobile, wireless communications, and fixed point-to-point microwave links. Our survey measured a mixed pattern of usage throughout these bands, including both intermittent and continuous signals.
79, 80	2300.0–2500.0	Signals from radiolocation, fixed and mobile services, broadcasting satellites, satellite radiolocation, amateur, mobile satellites, and radiodetermination satellites occupy this frequency range. General uses in this band are amateur radio, high-power long range surveillance radar, air-traffic control radars, telemetry, WAPA, research and developmental testing, ISM equipment (such as microwaves), downlinks, and the Arecibo radar (which operates from 2370 to 2390 MHz). There are wireless communications in this band, military tactical communications, TV auxiliary broadcasting, private land mobile, fixed microwave, scientific balloon-borne payloads, Radio Frequency Identification (RFID), and U.S. Coast Guard crew communications. In the graph we see different characteristics for the signals transmitting from 2485.0 to 2495.0 MHz than for signals from 2340.0 to 2485.0 MHz.
80, 81	2500.0–2700.0	These bands are allocated for fixed and mobile services, broadcasting, earth exploration, fixed and mobile satellites, radio astronomy applications, and space-research. The general utilizations in these bands are wireless communications, military tactical communications, NASA-research on global environmental changes and downlinks, earth exploration satellite, passive space research, radio astronomy. Most of these signals appear to be digitally modulated.
82	2700.0–2900.0	The only allocations in this frequency range are for aeronautical radionavigation services and meteorological aids. Airport Surveillance Radars (ASRs) and Next-Generation Radar (NEXRAD) weather radars operate in this band and there is some radio astronomy research in this band. The graphs shown on this page show a radar that switched to a different channel while we were at the measurement location. This measurement was taken using the stepped-spectrum algorithm used to detect radars. There are several distinct frequencies that show activity in this band in the Denver metropolitan area. They are at 2760 MHz, 2785 MHz, and 2825 MHz.

Figure(s)	Frequency Range (MHz)	Notes
83-88, 92	2900.0–3700.0	Radiolocation, maritime and aeronautical radionavigation, and fixed services and fixed satellite services are assigned to this band. There are secondary allocations from 3100.0 to 3300.0 MHz for earth exploration satellites and space research. The general utilizations are maritime radars, military high-power radars, long-range surveillance radars, private land mobile, SARS, amateur radio, and satellite communications. Swept measurements (Figures 83-88) were made from 2900.0 to 3700.0 MHz and stepped-spectrum measurements (Figure 92) were made from 2900.0 to 3650.0 MHz (a radar band). The swept measurements showed little activity; we see only one trace where activity was prevalent in Figure 92. In the frequency range from 3100 to 3600 MHz, the spectrum appears mostly inactive using the swept-frequency algorithm, but shows one distinct trace with activity and for the rest of the traces shows low-level frequency activity when measured using the stepped-spectrum algorithm. This demonstrates how different measurement techniques can impact our understanding of the signals that occupy the spectrum.
89-91	3700.0–4200.0	The allocations in this frequency range include fixed, fixed-satellite, and mobile. Satellite communications, fixed microwave and reception of downlinks are the general utilizations for this band. The downlink signals are paired with transmission of uplink signals from 5925 to 6425 MHz. We measured little activity in these bands.
93, 95	4200.0–4400.0	The only allocation in this band is for aeronautical radionavigation services. CW and pulsed radar altimeters are used in this band. We measured these altimeters while conducting an azimuthal-scan in the 4000–5000 MHz band. Figure 93 shows the altimeter signals in the 4000–5000 MHz band with other signals and Figure 94 shows a close-up of an altimeter band from 4200 to 4400 MHz. Our zero-degree position in Figure 94 was lined up with magnetic north, whereas the Google Earth© images in Figures C-1 and C-5 in Appendix C are aligned to true north. The declination during this measurement was approximately 9°. The measured signals appear at approximately 10° which would correspond to altimeter readings that may have come from Rocky Mountain metropolitan airport in Broomfield, CO. The measured signals located between 70° and 110° correspond to altimeters that may be located at Denver International Airport in Denver, CO. We believe these are altimeters because they appear between 4250 MHz and 4350 MHz.
93, 96	4400.0–5000.0	The allocations in this frequency range are for fixed, mobile, and fixed satellite services, radio astronomy, and space research. There is a 10 MHz allocation from 4990 to 5000 MHz for “RADIO ASTRONOMY” for passive space research. The general uses are tactical systems for point-to-point, line-of-sight and troposcatter communications, unmanned aerial video downlinks, space-to-earth communications, public safety land mobile, drug interdiction, radio astronomy, passive environmental change observations and measurements, radio astronomy, and very long baseline interferometry. There are few detected signals in this band in the Denver metropolitan area.
97	5000.0–5250.0	The allocations for this frequency range are aeronautical radionavigation and mobile services, radionavigation and fixed satellite services, and mobile communications. The general uses in this band are aviation, satellite communications. The FAA and the military use this band for the MLS and the Airport Network and Location Equipment (ANLE) system. The ANLE is a high-integrity, high data-rate wireless local area network (WLAN). RF devices also have assignments in this band. We measured a distinct continuous-use signal at approximately 5190 MHz.

Figure(s)	Frequency Range (MHz)	Notes
97, 98, 100	5250.0–5925.0	This frequency range is allocated for earth exploration and fixed satellite services, radiolocation, space research, aeronautical and maritime radionavigation, meteorological aids, and mobile services. The secondary allocations from 5650.0 to 5925.0 MHz are for amateur and amateur satellite services. The general utilizations in this band are for RF devices, private land mobile, military radars, space-based observations, SARs, active radio astronomy research, aviation, ground-based meteorological radars, maritime communications, Terminal Doppler Weather Radar (TDWR) systems, ISM equipment, amateur radio, and personal radio. This area of the spectrum was also measured using the stepped-spectrum algorithm as shown in Figure 100. The signals at approximately 5520, 5615, 5725, and 5850 MHz shown in the swept-spectrum measurements of Figures 97 and 98 show up in the stepped-spectrum measurements of Figure 100 as well.
98-103	5925.0–7250.0	The allocations across this frequency range are for fixed, fixed satellite, and mobile services. The general utilizations in this band are earth-to-space satellite communications, fixed point-to-point microwave, Federal civilian and military satellite communication uplinks (paired with 3700–4200 MHz), TV broadcast auxiliary, cable TV relay, remote sensing (6425–7250 MHz), radio astronomy (6668.518 MHz). Federal agencies use the band from 7125 to 7250 MHz for point-to-point microwave communications, weather, vessel traffic, hydroelectric and space research (7190–7235 MHz). Figures 101 and 103 show azimuth-scanning measurements. True point-to-point links appear as small dots on the plot at several angles but one frequency. Other transmission types, such as digital signals, show strong signals at all angles within some frequency span. Microwave links have low power that is not measured by the swept-spectrum algorithm; we would expect the point-to-point links captured in Figures 101 and 103 to be transmitting all of the time.
102-107	7250.0–8500.0	Most of the allocations across these frequency bands are for Federal assignments and include fixed, mobile, earth exploration and meteorological satellites, and space research. The secondary allocations are for fixed services and mobile satellite services. Non-federal allocations are for space research. The general utilizations for these bands are space-to-earth communications, Defense Satellite Communications Systems (DSCS), fixed point-to-point microwave systems, weather, vessel traffic, hydroelectric and space research, Wideband Gapfiller Satellite (WGS), GOES, TTC data downlinks from non-geostationary satellites, long-range radars, deep space probes communications. The measurements were taken using both swept-spectrum methods (Figures 102, 104, and 106) and azimuth-scanning measurements (Figures 103, 105 and 107). We measured very little activity in these bands.
106-109	8500.0–10000.0	In this final measured frequency range, the allocations are for radiolocation, aeronautical and maritime radionavigation, and radionavigation services. Secondary allocations are for radiolocation and meteorological aids. The general utilizations are military and non-military radar systems, private land mobile, earth-exploration satellites from 8550 to 8650 MHz, search and rescue, law enforcement, navigation, surveillance, avian detectors, airport surface detection, maritime harbor and coastal traffic, meteorological radars, airborne radars to research convective storm and mesoscale phenomena, and SARs. Measurements in these bands were taken using the swept-spectrum techniques (Figures 106 and 108), stepped-spectrum methods (Figure 109), and azimuth-scanning methods (Figure 107). Activity was measured at 9370 MHz using both swept- and stepped-spectrum methods.

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APPENDIX A: EXPLANATION OF MEASUREMENT GRAPHS

There are many ways to process and present the data acquired during spectrum surveys. In this section, three methods employed at ITS during this survey will be discussed.

A.1 Maximum-Mean-Median-Minimum (M4) plots

The M4 plots (top graph of Figure 3 in Section 3) show the maximum, mean,[4] median, and minimum values at each frequency, and are calculated using internal MATLAB® scripts. The measured data are expressed in field strength (dBµV/m), referenced to the input of a 0 dBi antenna versus frequency. The measured data is corrected using the system gain and the antenna correction factor (ACF). The system gain and noise figure are obtained by performing calibrations periodically throughout the measurement series. The mean system noise (magenta line) is produced using the noise figure from the calibrations.

A.2 Time vs. Frequency Plots

Time vs. frequency (waterfall) plots are displayed using a contour plot as shown by the middle plot of Figure 3. The generation of waterfall plots is time and memory intensive due to the large array sizes. This array is decimated by determining the median measurement time between each scheduled measurement and retaining the maximum power trace for that time interval. The time axis displays the total measurement time for all traces in minutes. The maximum value of this axis will vary depending on the number of times the event was measured. The data spacing stated at the top of the graph refers to the median number of minutes between measured events. For the data shown in Figure 3, the median time is 16.4 minutes, which means the data was measured approximately every 16.4 minutes. The threshold, shown in the bottom plot, determines the lowest field strength level in decibel-microvolts per meter (dBµV/m) at which data will be displayed in the time-varying plot. If the measured field strength does not exceed the threshold, the data point will not be displayed (it will be rendered as a white point). If the data exceeds the threshold, the color of the data point represents the amplitude of the field strength—blue represents the lowest field strength and red represents highest field strength. The time scale creates a linear time vector using the median time spacing for the time interval mentioned above.

The threshold is determined by one of two methods. One method requires a statistical analysis of the system noise. With this technique the threshold is set to a field strength level at which the system noise is likely to exceed the threshold 0.01% of the time. The second method is determined by first processing the data into M4 plots and examining the maximum value of the trace at frequencies that appear to be free of signals. The threshold level is then set to this maximum level.

[4] The mean is taken by converting power values to linear form. The mean of these linear values is determined and then converted back to power and then into field strength in dBµV/m.

A.3 Field-Strength, Complementary Cumulative Distribution Function (FS-CCDF) Plots

When measurement system components (amplifiers, switches, filters, SAs) perform consistently over the course of a measurement, the statistical characteristics of the system noise remain stationary with regard to the mean, variance, and power distribution. Though noise is a random process, its consistent statistical characteristics provide a useful way to differentiate system noise from signals, especially when the signal power is very close to the mean power of the system noise. Signals will have statistical characteristics that are different from those of noise.

In this report, we plot the FS-CCDFs as shown by the bottom graph in Figure 3. These plots are useful for differentiating between intentionally-radiated signals and impulsive or Gaussian noise, quickly characterizing signals, and identifying low-level signals—something that is not generally possible with other processing methods.[5] For these types of graphs, we begin by constructing the probability density function (PDF) of the measured data. In the current software, the measured data is binned into 0.1 dB power bins. From the PDF, we compute the cumulative distribution function (CDF), and the complementary cumulative distribution function (CCDF) vs. power in dBm.[6] From the CCDF shown in Figure A-1, we choose equally spaced values along the x-axis to obtain values of power or field strength at the input to the antenna on the y-axis. We also choose the spacing so that we get probabilities close to 0.1%, 2%, 50%, and 95%. By choosing equally-spaced x-values, it is possible to scale the y-axis so that sample-detected, Gaussian system noise is displayed as a straight line. The chosen values are converted to a percent probability. Finally, at each frequency, we display the probability that the power (dBm) or field strength (dBμV) on the y-axis is exceeded, as shown in Figure A-2 or the figures in the report. Because this is a cumulative distribution at each frequency, the probability value gives us an indication of the percentage of time that the signal appeared above certain power levels during the measurement. For other signal types, the spacing of the power or field strength values will be indicative of the signal type or the type of detector used to measure the signal. For example, median-of-five processed Gaussian noise (Figure 42, 411.2–411.3 MHz) show a probability-level spacing of approximately one dB (Figure A-2). RMS-detected Gaussian noise (Figure 69, 1210–1230 MHz) show the lower-probability levels (0.09% to 2.02%) more widely spaced than higher probability levels (93.30% to 96.18%) (Figure A-2).

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[6] CCDF's are calculated using powers which are then converted to field strength in dBμV/m for the final plots.

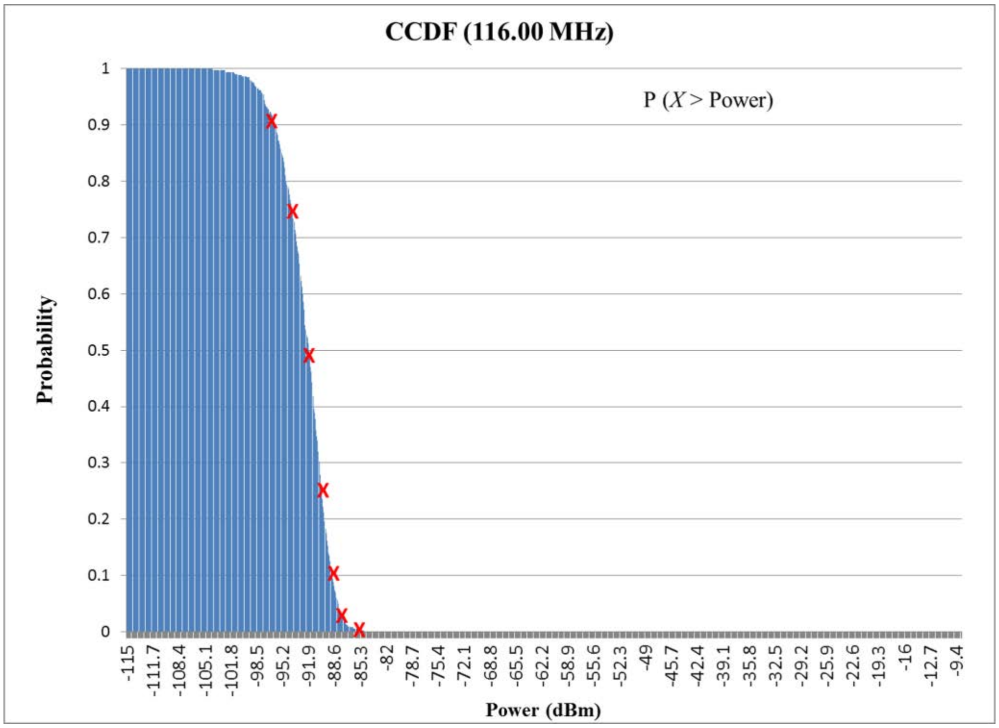

Figure A-1. Complementary cumulative distribution function (CCDF) at 116.00 MHz.

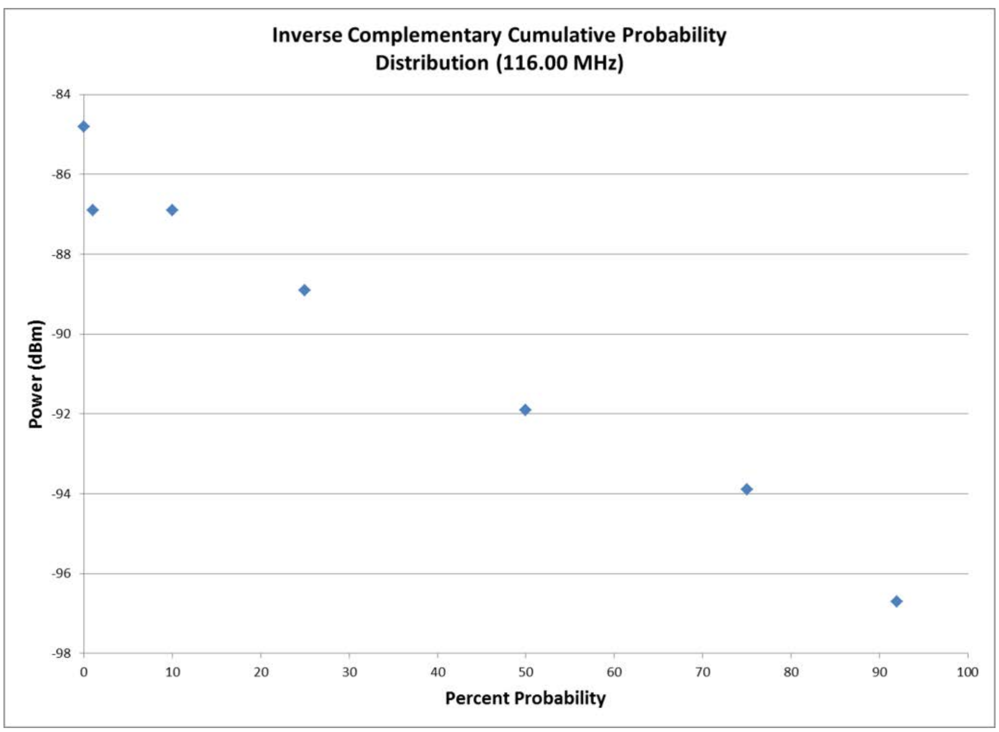

Figure A-2. Inverse complementary cumulative distribution function. The percent probability is shown along the x-axis and the power is shown along the y-axis.

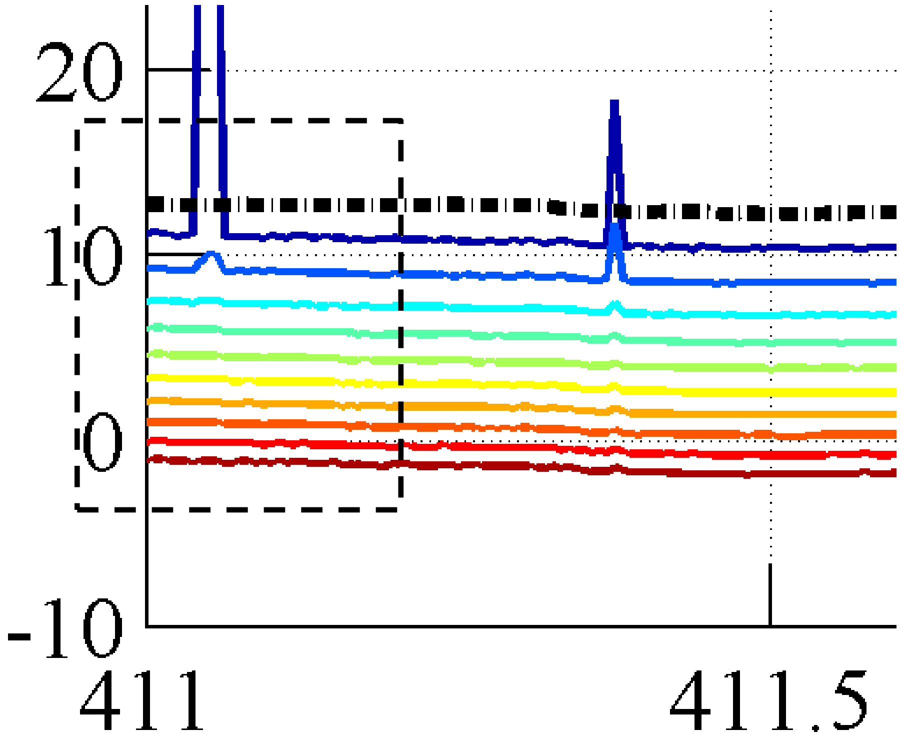

Figure A-3. Close-in view of one-dB probability spacing for median-of-five processed Gaussian noise shown inside the dashed rectangle for the frequency range from 411.2 to 411.4 MHz.

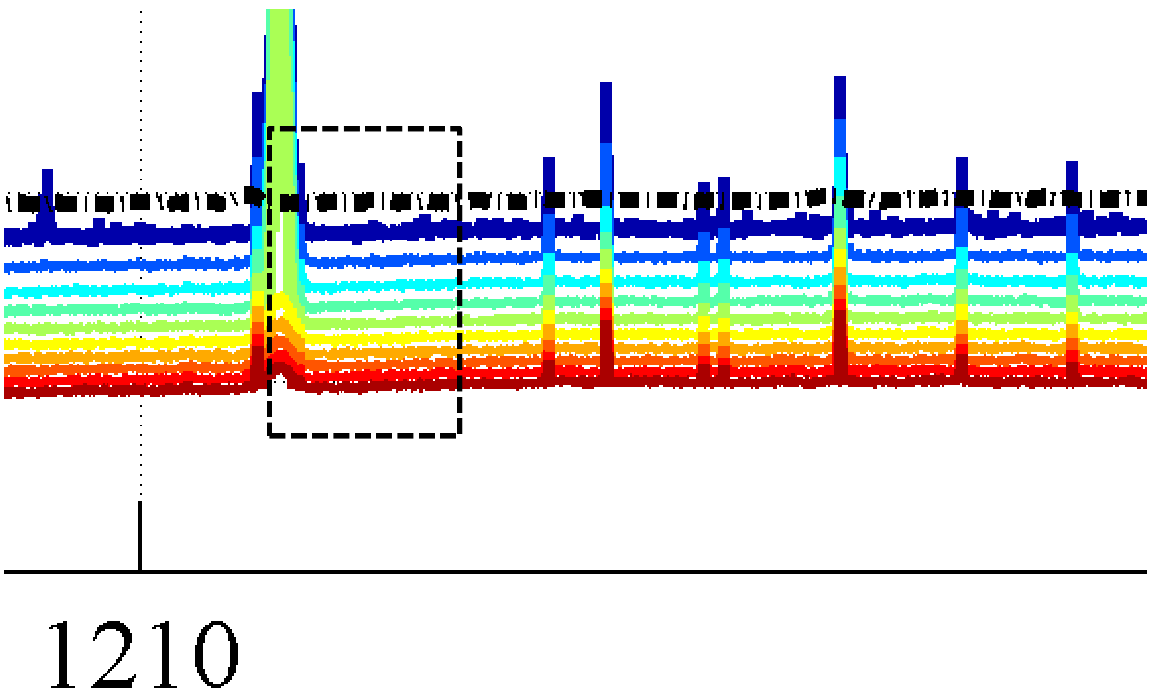

Figure A-4. Close-in view of variable probability spacing for RMS-detected Gaussian noise shown inside the dashed rectangle for the frequency range from 1210 to 1230 MHz.

APPENDIX B: RADIO SPECTRUM MEASUREMENT SCIENCES (RSMS) SYSTEM

The NTIA RSMS-4 truck is a self-contained vehicle used to transport equipment to locations to perform spectrum surveys or detailed studies of various radio services. This vehicle, shown in Figure B-1, is approximately 4.8 m (16 ft.) long, has a gross weight of 11.6 t (12.75 ST), and is wired for 100-amp electrical service.

A two-layer design provides approximately 60 dB of shielding from outside radio sources. The outside skin is a riveted cage of 28.6 mm (⅛ in.) thick aluminum with fully welded seams. The wiring and conduit are surface mounted and do not pierce the skin. Bulkhead feed-throughs provide access to the masts on the exterior of the truck. The doorway is equipped with finger stock to ensure good electrical contact to improve shielding effectiveness. The masts can be extended to a height of 9.1 m (30 ft.) using an internal compressor. Air conditioning provides a constant temperature environment. A 20 kilowatt (kW) generator can be used to supply power for the truck when there are no power sources available. The generator runs off two 100-gallon fuel tanks. The truck can run 24 hours a day for approximately 1½ weeks before refueling. When a nearby power source is available, a 15 m (50 ft.) electrical cable with optional 15 m (50 ft.) extension can be used to connect to the source.

Measurement and processing equipment is placed in three slide-mounted racks each with its own uninterruptible power supply (UPS). Equipment for this spectrum survey is shown in Figure B-2. Additional storage is provided in compartments in the truck. An emergency escape is located on the side of the truck and is also shielded. A winch can be used to lift equipment onto the roof of the truck. A safe is located in one of the upright storage cabinets. Interior lighting consists of one overhead and one wall-mounted fluorescent fixture and three direct current (DC)-powered dome lights. Track lighting is installed in front of the equipment racks. A smoke/carbon monoxide detector and fire extinguisher are located in the truck at all times. A schematic of the RSMS truck is shown in Figure B-3.

Figure B-1. RSMS-4 measurement truck with mast-mounted antennas and preselector units.

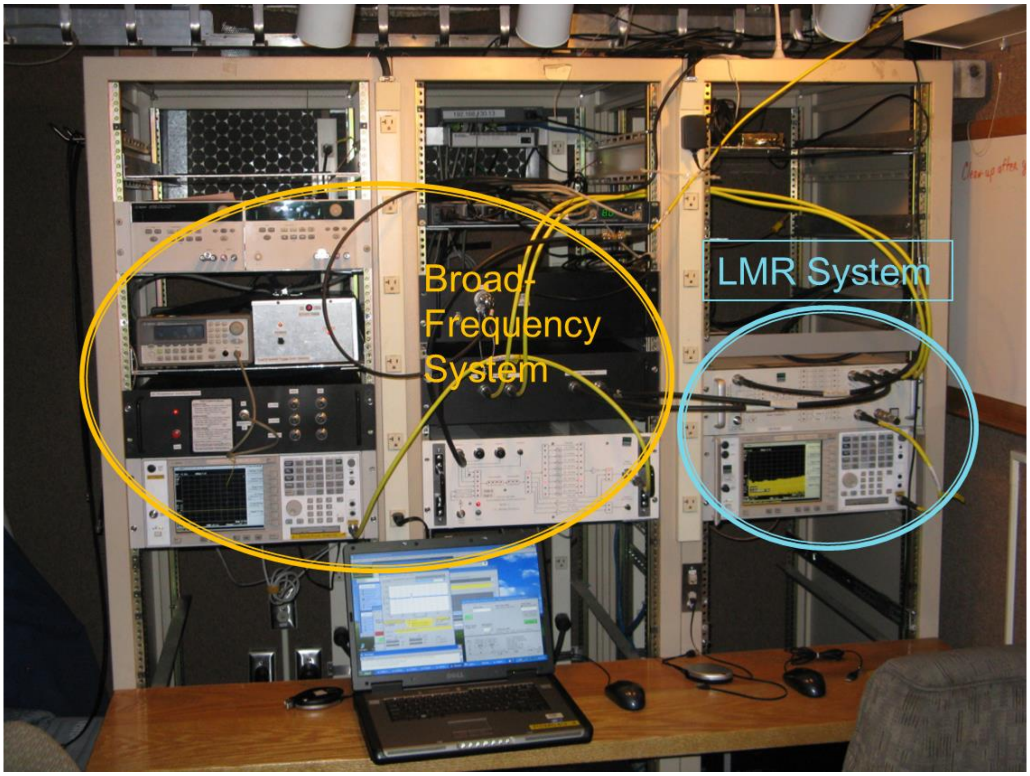

Figure B-2. Measurement equipment setup inside RSMS-4 truck. The LMR system makes measurements in the LMR bands and the broad-frequency systems measures all frequencies above 500 MHz and some bands not covered by the LMR bands

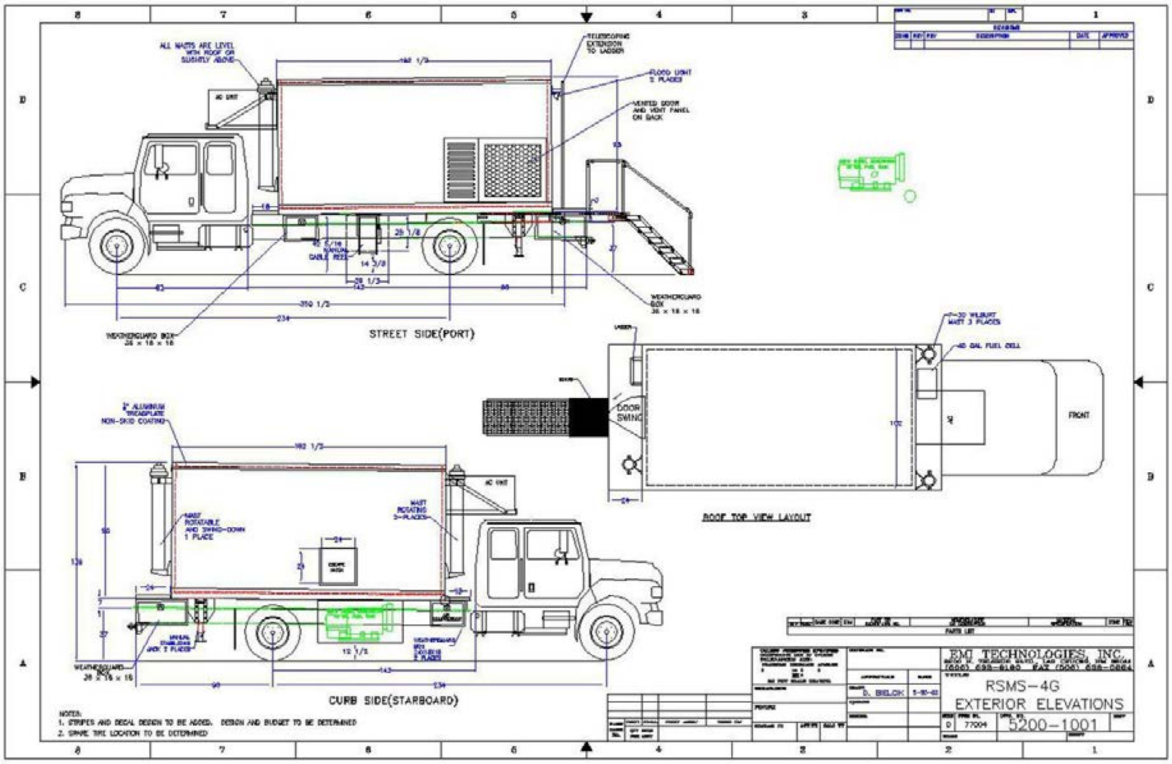

Figure B-3. Detailed schematics of the RSMS truck.

APPENDIX C: STATIC VS. MOBILE MEASUREMENTS

We would like to understand how static spectrum occupancy measurements compare to mobile measurements. We also want to understand how a measurement on a hilltop compares to a mobile measurement that covered the city of Denver. We present data for the static spectrum survey conducted from a hilltop, data collected around the immediate measurement site, and data collected over the city of Denver. We also show the spectrum occupancy measurement data at discrete time intervals to show the build-up of signals and approximately how long a measurement might take to acquire a large portion of the transmitted signals. We chose the LMR band from 406 to 420 MHz for this study.

C.1 Mobile Measurements in the Denver/Boulder Metropolitan Areas

Figure C-1 shows the route chosen for a mobile measurement in the Denver Metropolitan area. A GPS tracker is used to mark the route which is then imported into Google Earth© maps. Shown on this map are some key landmarks. The first is the location of the Arvada measurement site shown in about the middle of the map. Downtown Denver and the Denver International Airport (DIA) are labeled on the map as well. Other key locations are the Denver Federal Center and Buckley Air Force Base. The drive-path direction is shown by the white arrows and an explanation follows.

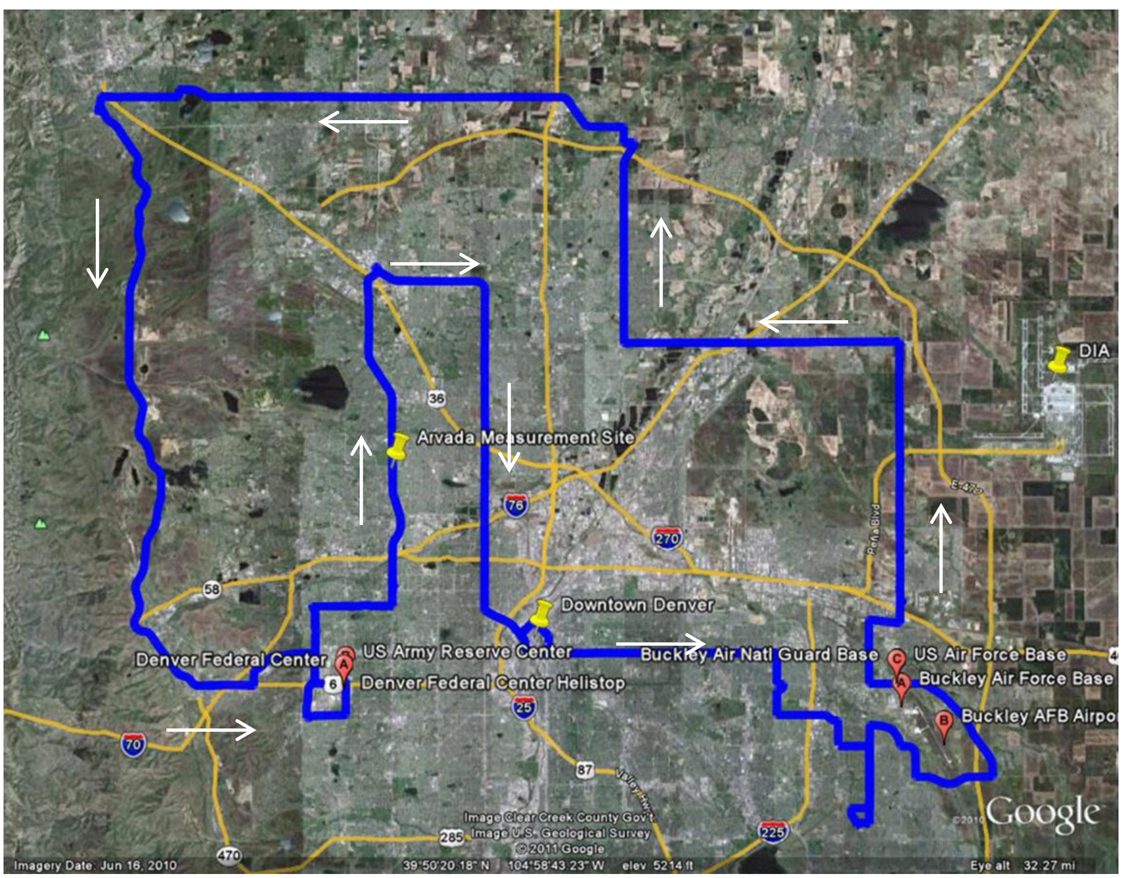

Figure C-1. Mobile measurement route for Denver/Boulder Metropolitan Areas.

We started driving in Boulder and drove down Highway 93 toward Golden. We then drove around the perimeter of the Denver Federal Center and headed north toward the Arvada measurement location. From Arvada we drove toward downtown Denver and drove some of these streets and then headed toward Buckley Air National Guard/Air Force Base. From this location we headed north toward DIA, turned left on 104th Ave and then headed north on Colorado Blvd. and then took Highway 7 toward Boulder to end the day.

Cumulative measurement results for this route are shown in Figures C-2–C-4. The first band measured is 406–411 MHz, the second band measured is 411–416 MHz, and the last band measured is 416–420 MHz. The signals from the 406–411 MHz band are LMR control channels and were on during the entire drive across the Denver Metropolitan area. We see that the median time in the waterfall plot was 1.65 minutes and that the entire drive took approximately 400 minutes or almost seven hours.

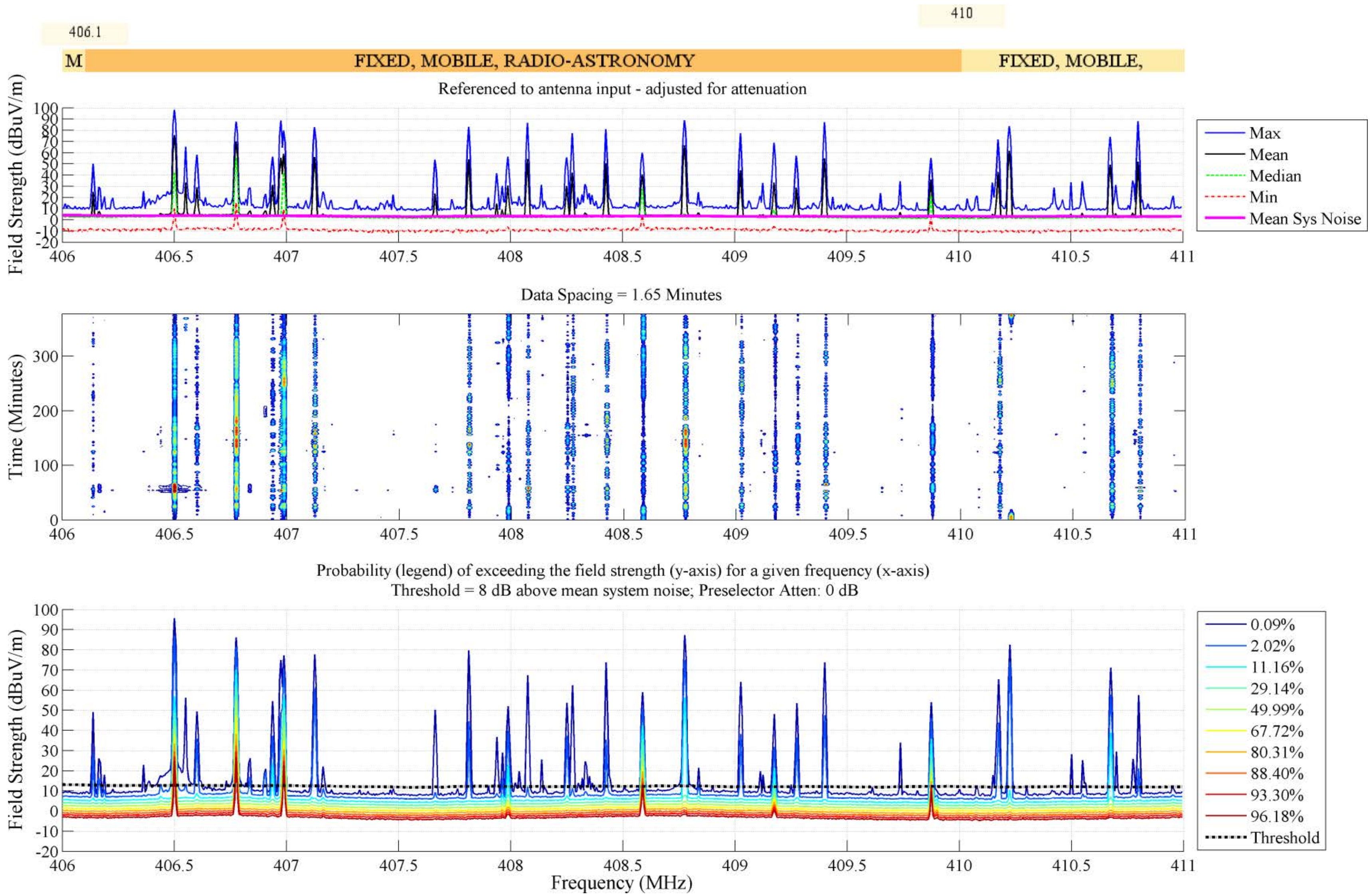

Figure C-2. Mobile measurements from 406 to 411 MHz in the Denver Metropolitan area.

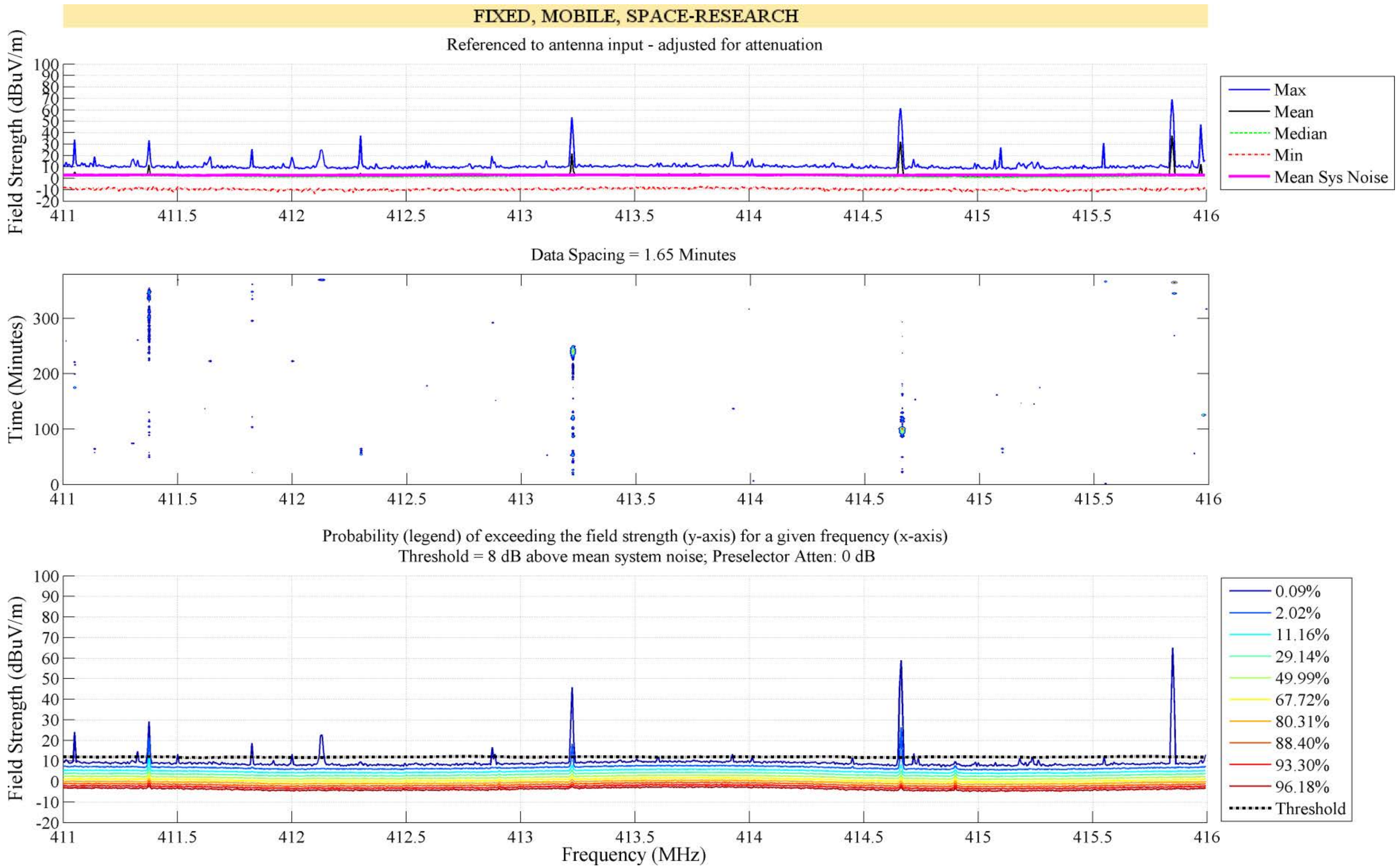

Figure C-3. Mobile measurements from 411 to 416 MHz in the Denver Metropolitan area.

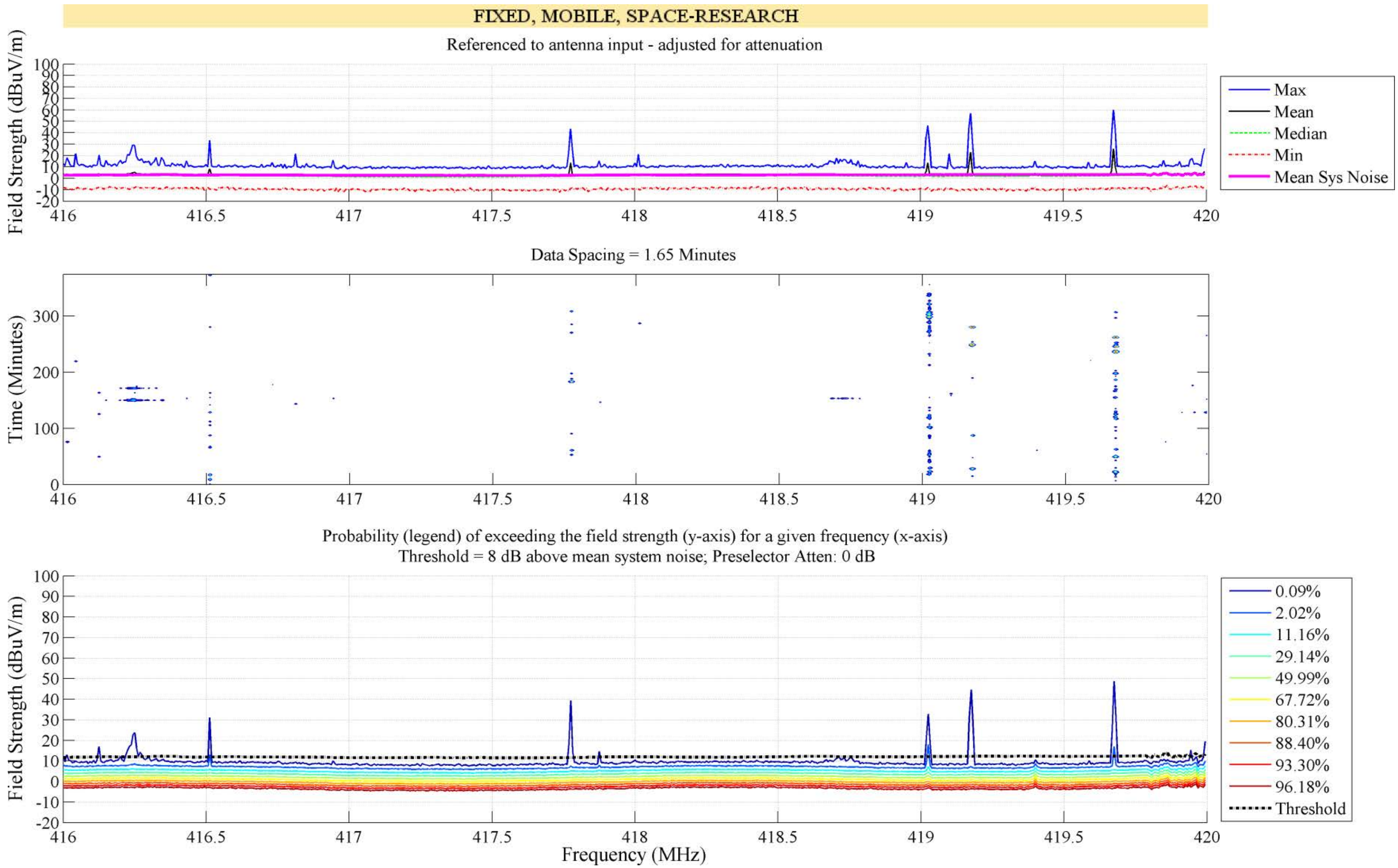

Figure C-4. Mobile measurements from 416 to 420 MHz in the Denver Metropolitan area.

C.2 Mobile Measurements around the Arvada Spectrum Survey Site

Figure C-5 shows the route chosen for a mobile measurement in the immediate vicinity of our location in Arvada, CO. We use a GPS tracker and then import the route into Google Earth© maps. Shown on this map is the location of the NTIA labs in Boulder, where we started and finished the measurement. Also shown is the Arvada spectrum survey site. We wanted to measure only signals around the Arvada site, so we traveled on rural and suburban streets around Arvada.

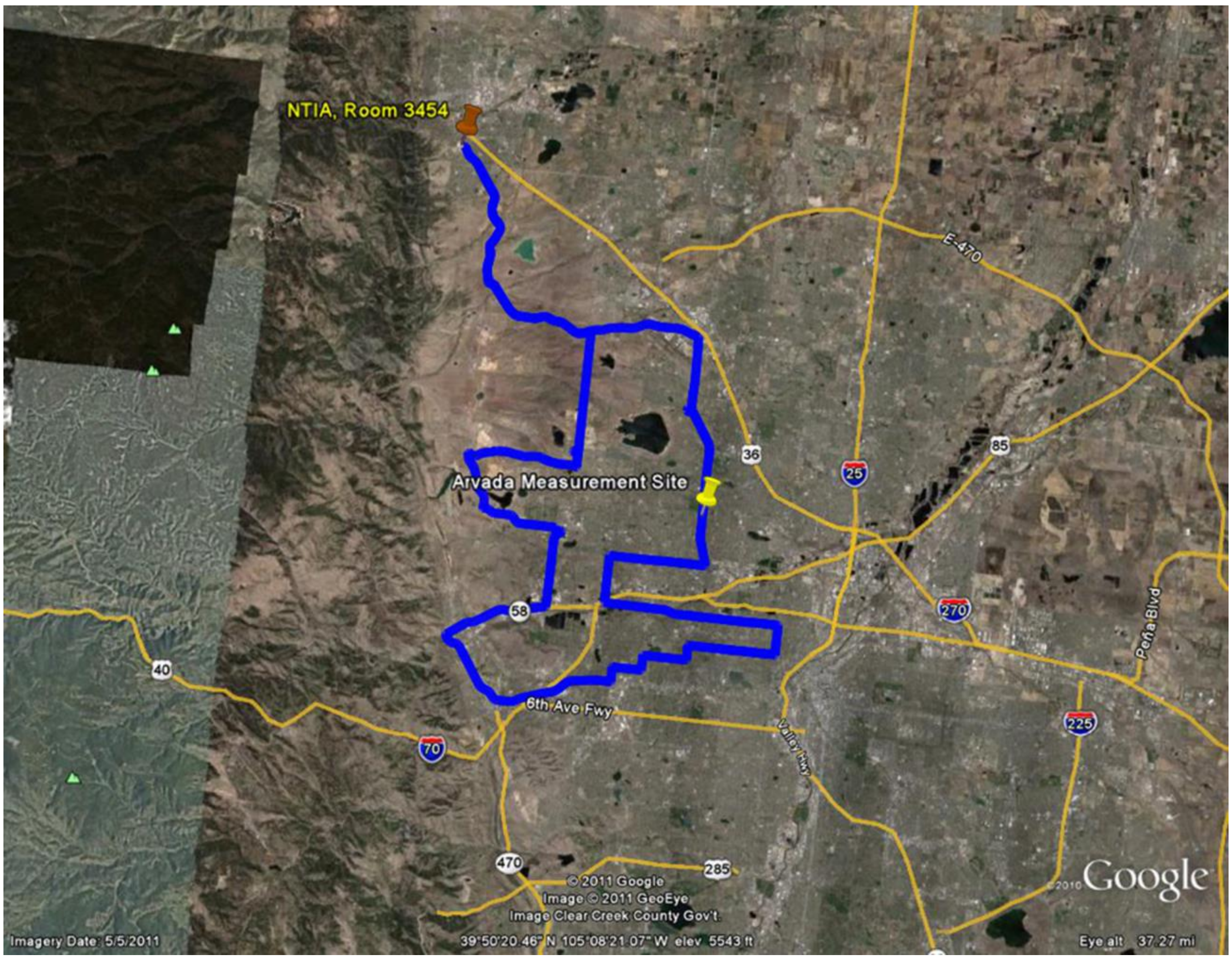

Figure C-5. Mobile measurement route for the Arvada suburbs.

Cumulative measurements at the Arvada location are shown in Figures C-6–C-8. The median time is 1.65 minutes and the total measurement time is approximately 175 minutes or almost three hours. For the most part, we see that many of the signals present in the Denver mobile measurements are present in these measurements. One major difference in these measurements is that some type of impulsive signal (0.09% trace separated from all other traces) was present across all three bands in the Arvada measurements. Both data sets were processed using the same methods, so at present this difference is being studied.

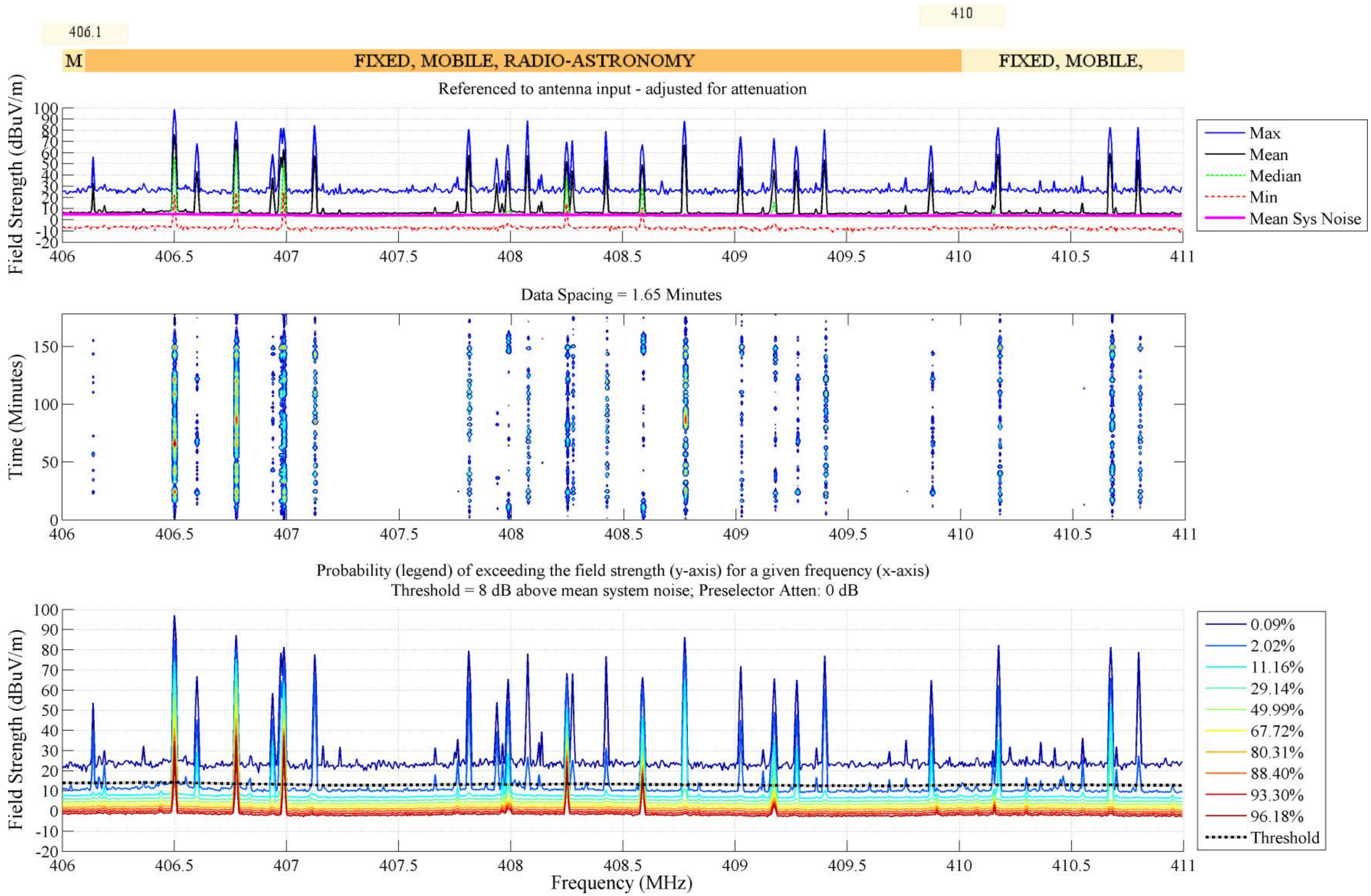

Figure C-6. Mobile measurements from 406 to 411 MHz around the Arvada spectrum survey site.

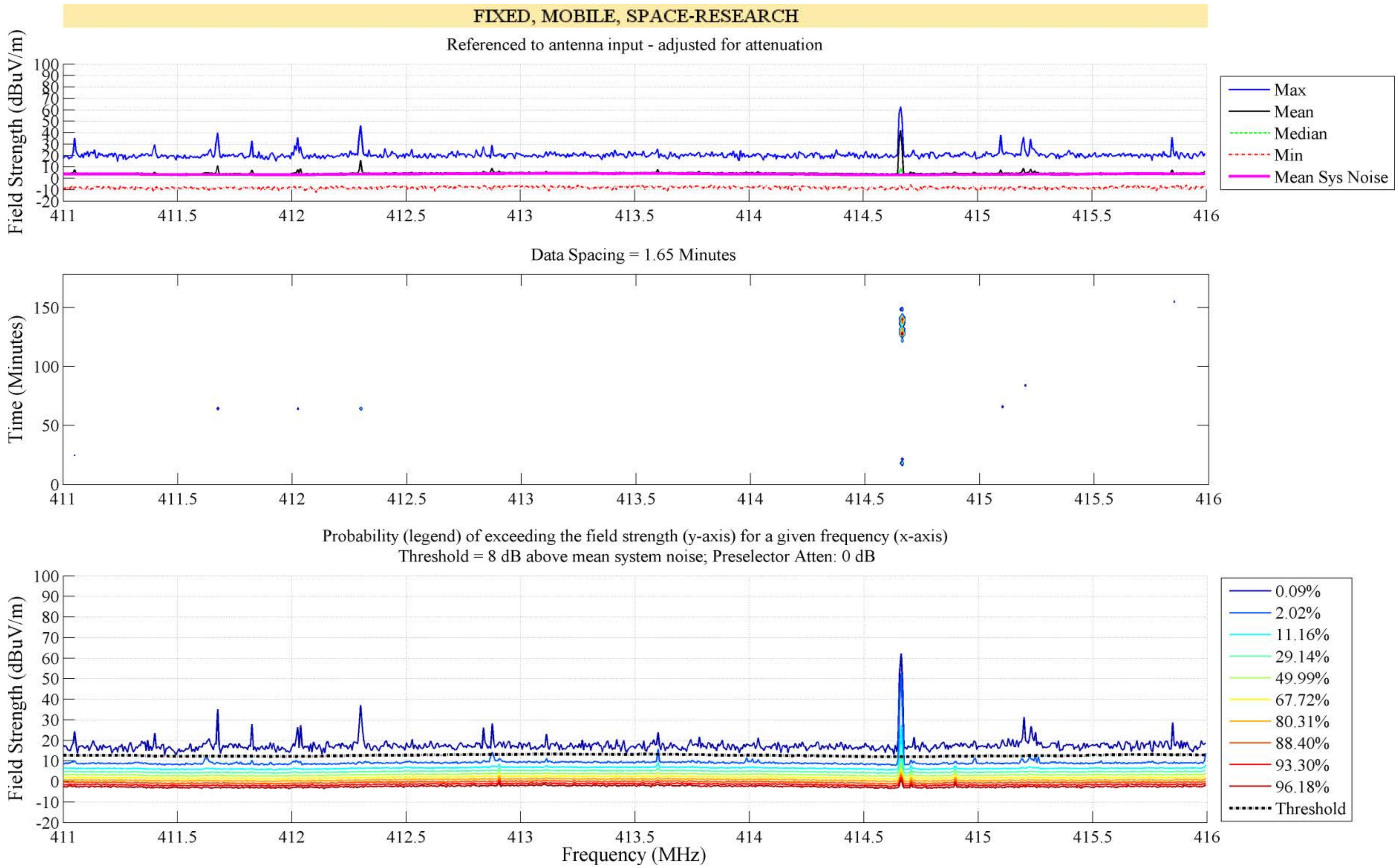

Figure C-7. Mobile measurements from 411 to 416 MHz around the Arvada spectrum survey site.

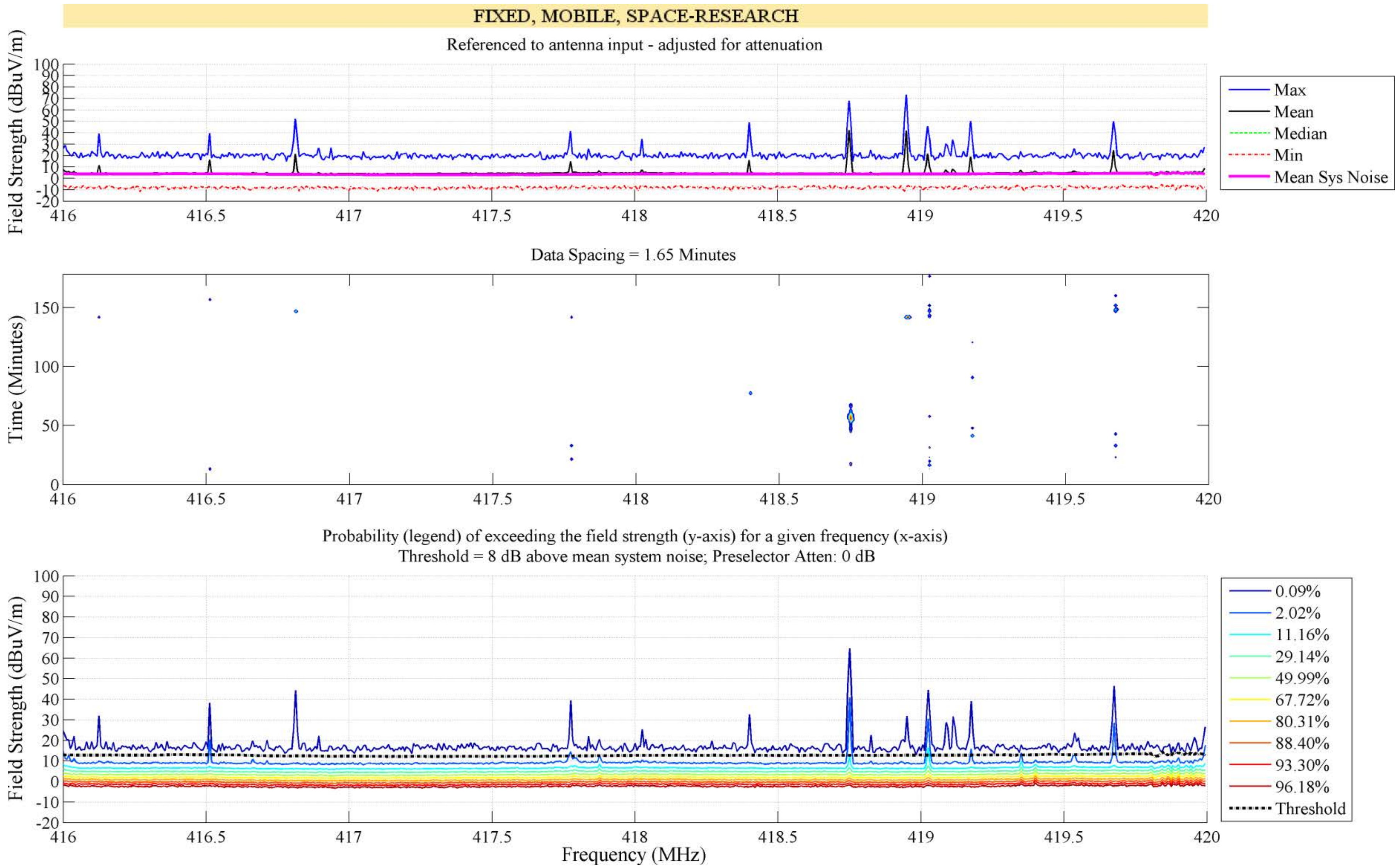

Figure C-8. Mobile measurements from 416 to 420 MHz around the Arvada spectrum survey site.

C.3 Static Measurements at the Arvada Measurement Site

We processed data in different time slots for the spectrum occupancy measurements shown in Figures 41–43. These plots have been duplicated in Figures C-14, C-19, and C-24. We wanted to investigate signals that appear during certain periods of time and compare them to the mobile measurements. We broke the static measurements into time slots. Measurements were made from June 1 to 29, 2011. We processed data for a random two week period from June 15 to 29, 2011. Within this two-week period, we processed data from June 17 to 24, 2011. During this week-long period, we processed data for a day-long period on June 19, 2011 and finally, we processed data on this day for a one-hour period from 7 a.m. to 8 a.m. All of these choices were random. A schematic of this is shown in Figure C-9.

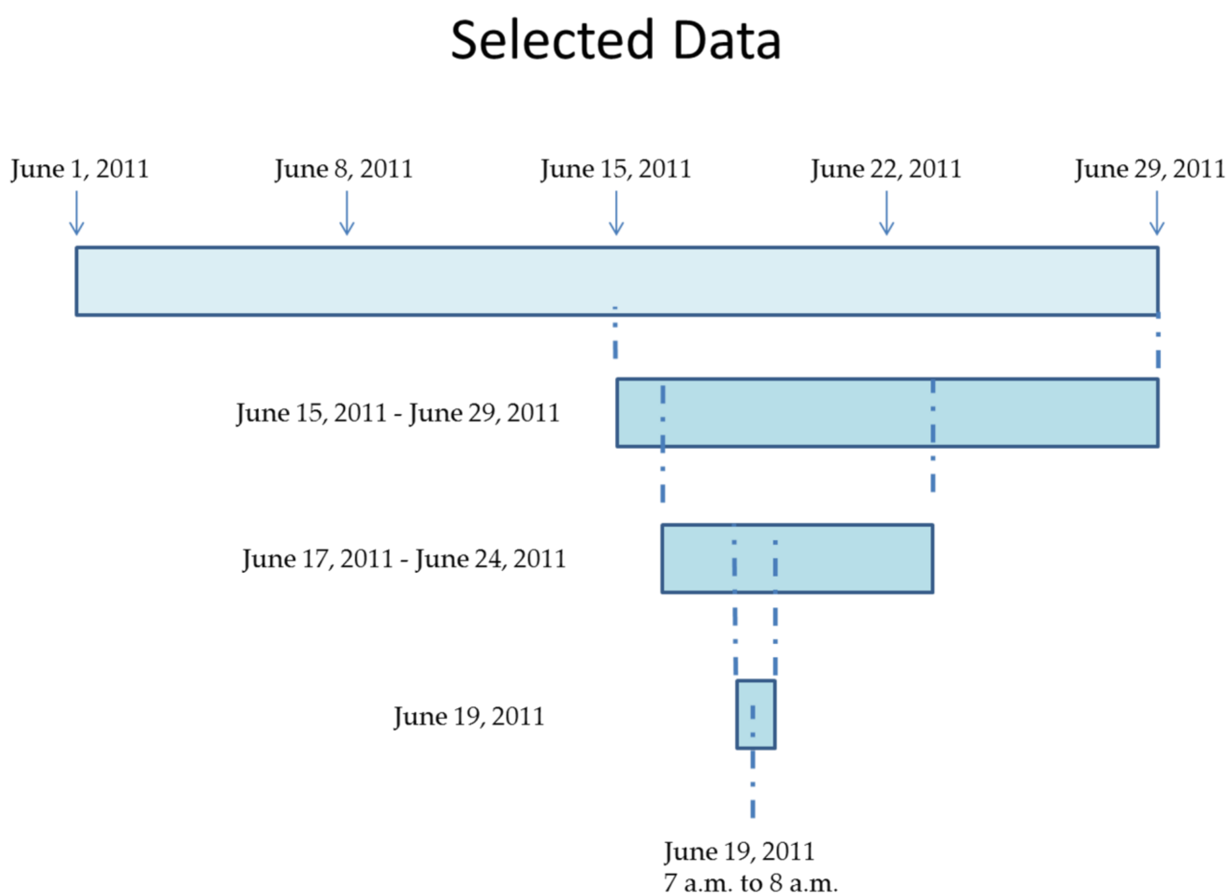

Figure C-9.Time slices chosen for processed data from the Denver spectrum survey in June 2011.

The results of this time slice processing are shown in Figures C-10–C-24. Figures C-10–C-14 show the results for the 406–411 MHz frequency band. Figure C-10 shows results for the one-hour time slice which shows a total of 31 frequencies that were acquired during this hour. Results for one day are shown in Figure C-11, showing an additional 15 frequencies captured during the day. An additional eight frequencies appear during the week as shown in Figure C-12.

One additional frequency appears during the two-week period, shown in Figure C-13, and four additional frequencies appear during the entire month as shown in Figure C-14.

Results for the frequency band 411–416 MHz are shown in Figures C-15–C-19. Six frequencies are shown during the one-hour time slice in Figure C-15. Transmissions from two large signals and several smaller signals are added to this frequency band during the day as shown in Figure C-16. Seven additional frequencies are transmitted during the week-long period as shown in Figure C-17. Figure C-18 shows results from the two-week period where an additional nine transmission signals are added to this frequency band. From two weeks to four weeks (Figure C-19), an additional five transmissions are added to this frequency data.

Figures C-20–C-24 show results for the frequency band 416–420 MHz. During a one-hour time slice, Figure C-20, six frequencies appear on the plot. Figure C-21 shows results for transmission received during the day in which at least nine new frequency transmissions appear. During the one-week period, 28 additional frequency transmissions are received as shown in Figure C-22. At least four more transmissions are recorded and a definite pattern begins to emerge from the noise on the waterfall plot from 419.5 to 420 MHz after an additional week (Figure C-23). Finally, from two weeks to four weeks, shown in Figure C-24, a few new signals appear between 418 MHz and 418.5 MHz, and a much broader signal appears in the waterfall plot between 419 MHz and 420 MHz.

C.4 Comparisons between Mobile and Static Measurements

In the 406–411 MHz frequency band, it appears as though measurements processed during a one-day time slice (Figure C-11) are comparable to measurements taken in the two mobile measurement scenarios (Figures C-2 and C-6). The characteristics of the signals may change; however, the frequency of transmission appears to be similar.

It appears as though many transmissions collected for the mobile measurements compare well with those measured in the one-week to two-week time slices for the frequencies from 411 to 416 MHz. The transmissions appear to differ both in field-strength levels and in the clusters of frequencies that appear. These transmissions are shown in Figures C-3, C-7, C-17 and C-18.

Some of the same signals appear in the three different measurements made in the 416–420 MHz band as shown in Figures C-4, C-8, and -21. A similar number of signals are shown in these three figures which is understandable since Figure C-21 shows signals for a one-day measurement. A few of the signal characteristics are different for the mobile measurements made across the Denver Metropolitan area.

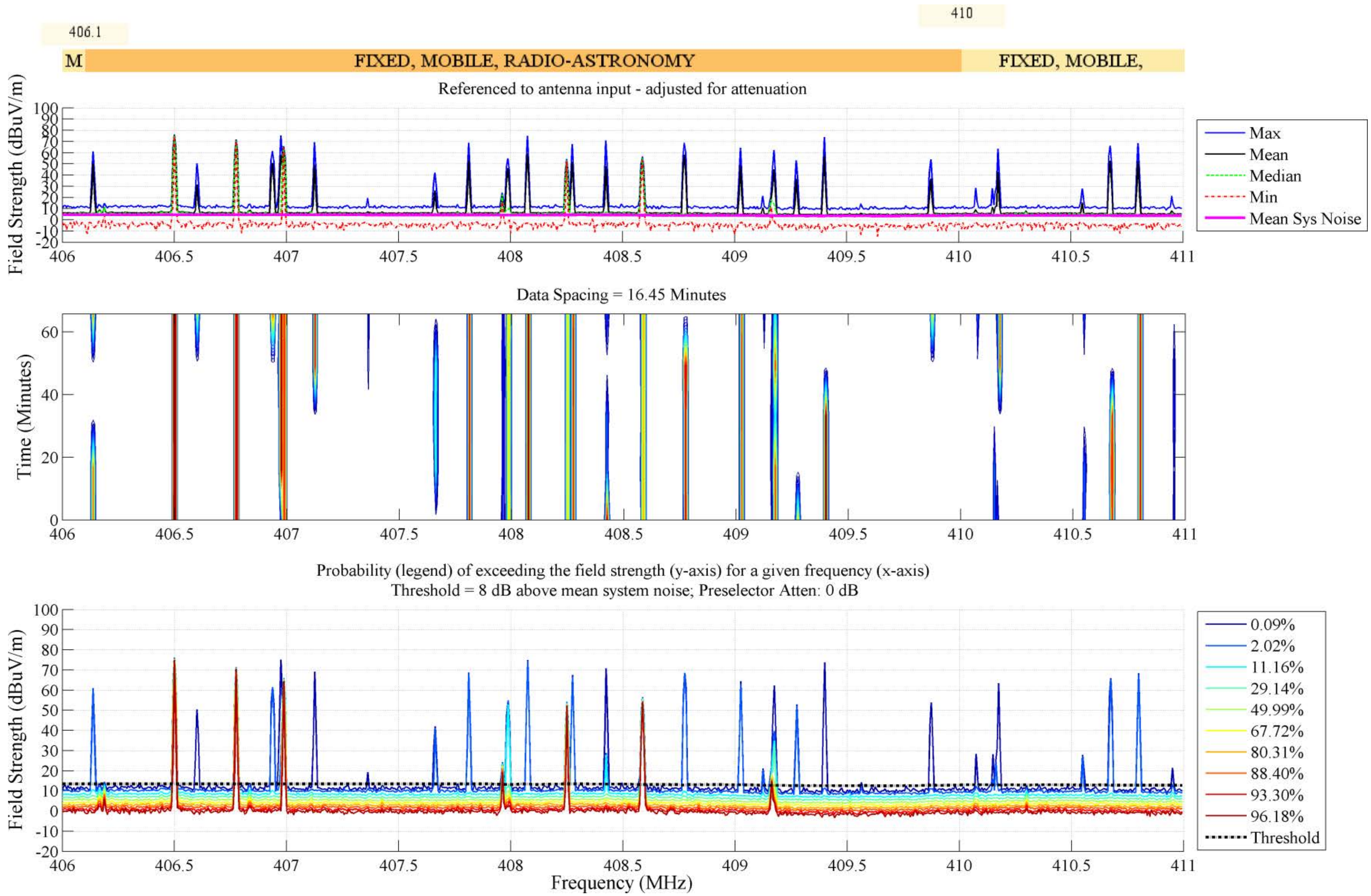

Figure C-10. Static spectrum survey measurements from 406 to 411 MHz processed over a one-hour time slice.

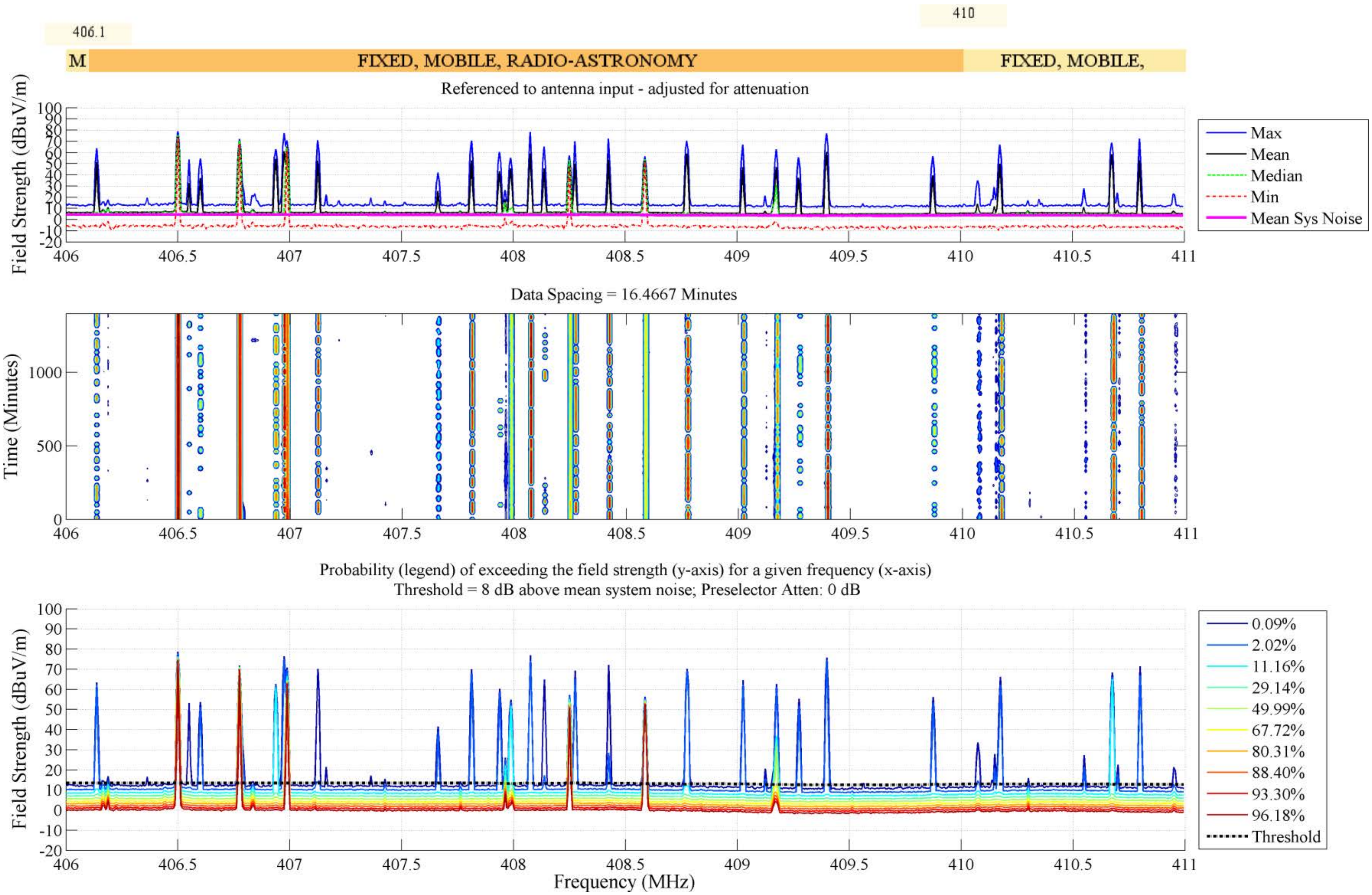

Figure C-11. Static spectrum survey measurements from 406 to 411 MHz processed over a one-day time slice.

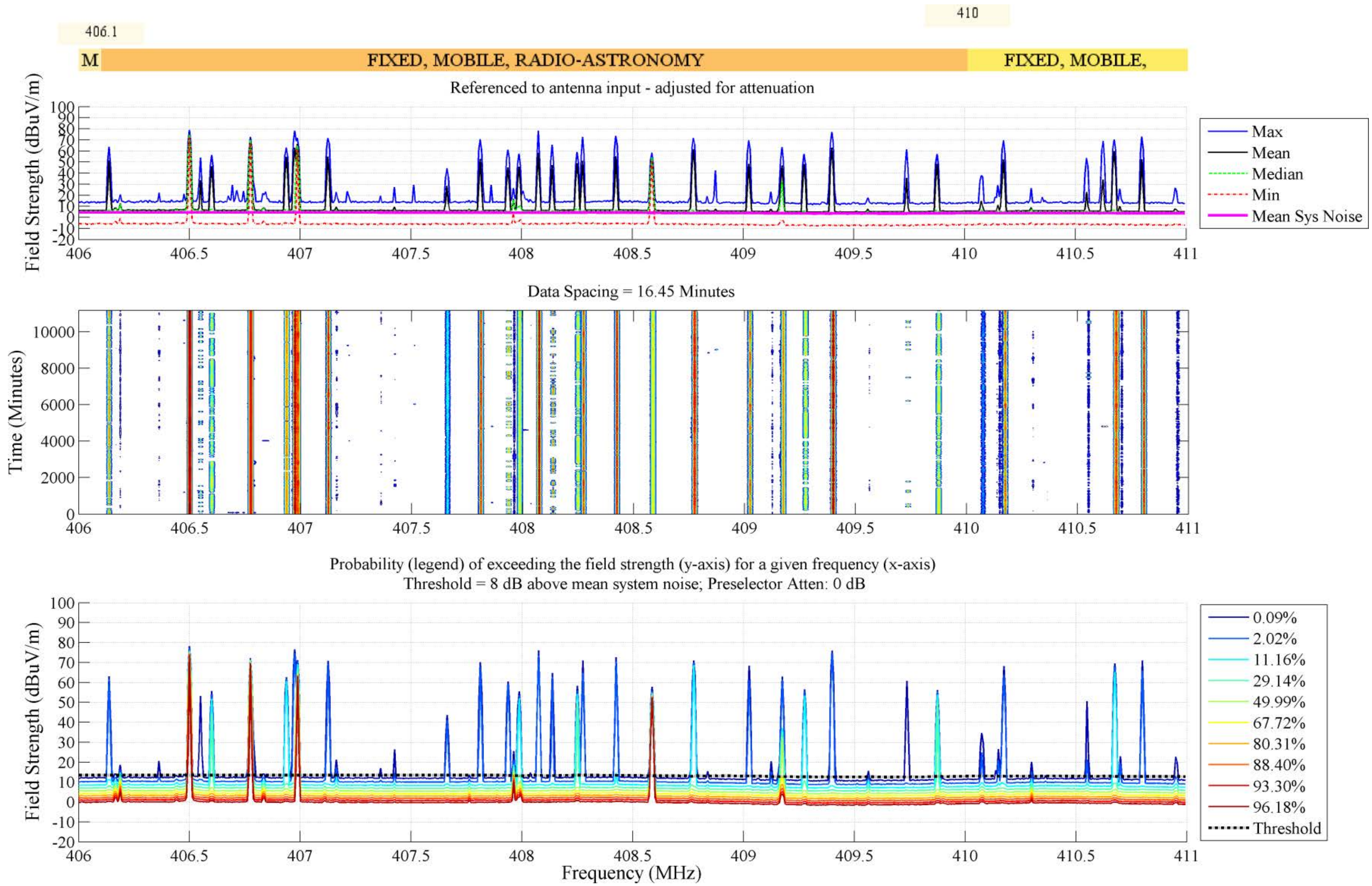

Figure C-12. Static spectrum survey measurements from 406 to 411 MHz processed over a one-week time slice.

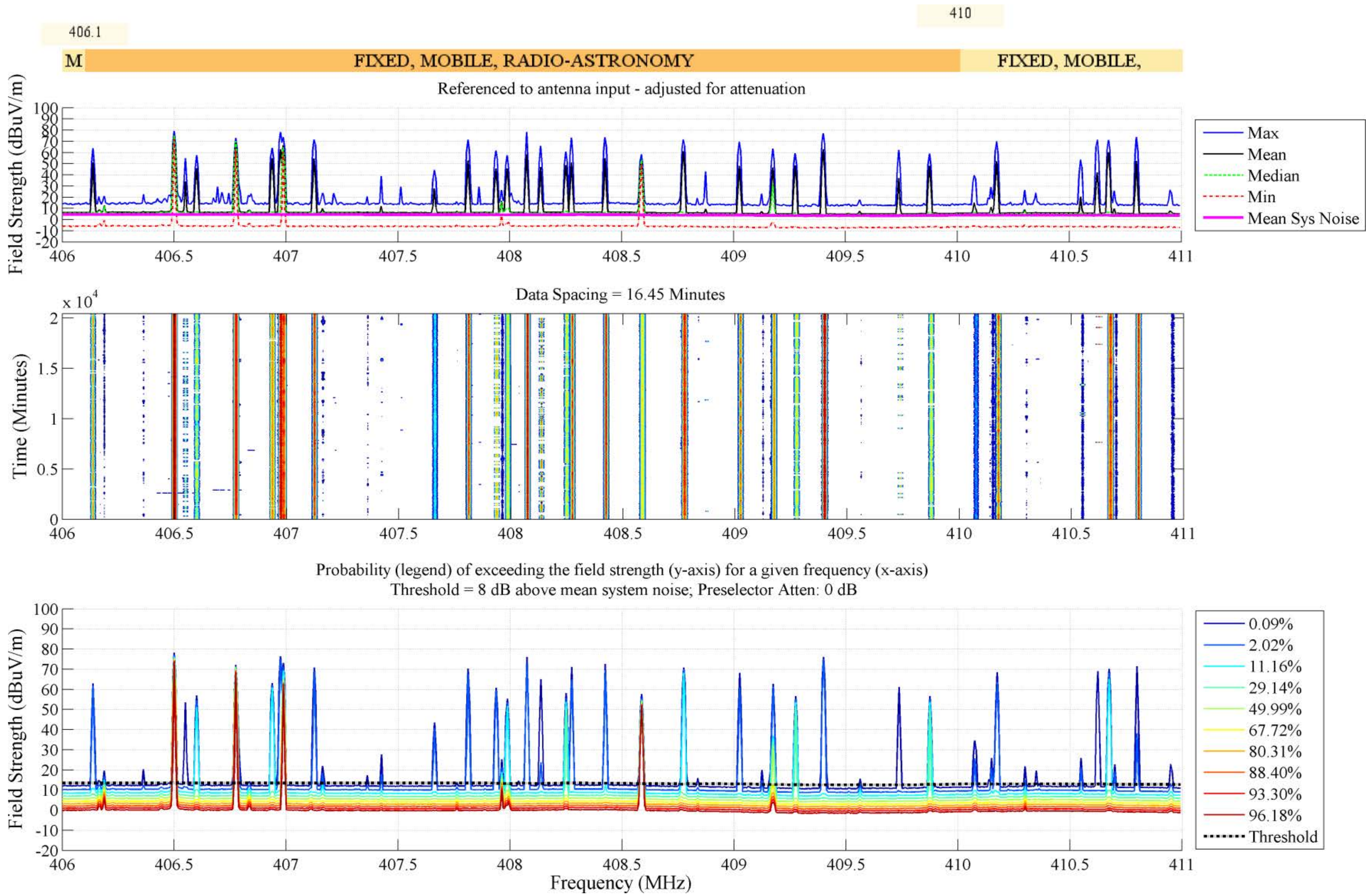

Figure C-13. Static spectrum survey measurements from 406 to 411 MHz processed over a two-week time slice.

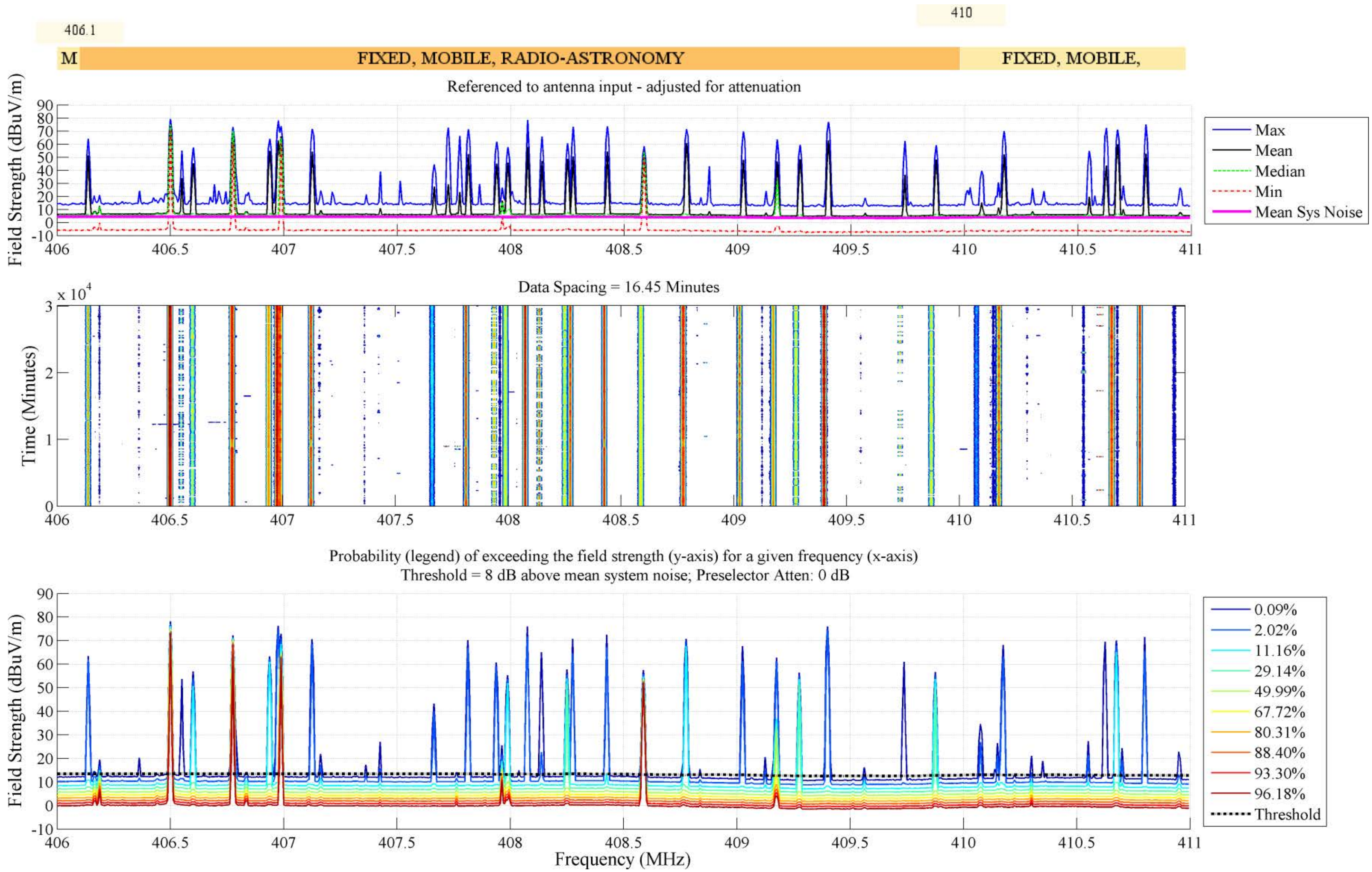

Figure C-14. Static spectrum survey measurements from 406 to 411 MHz processed over a one-month time slice.

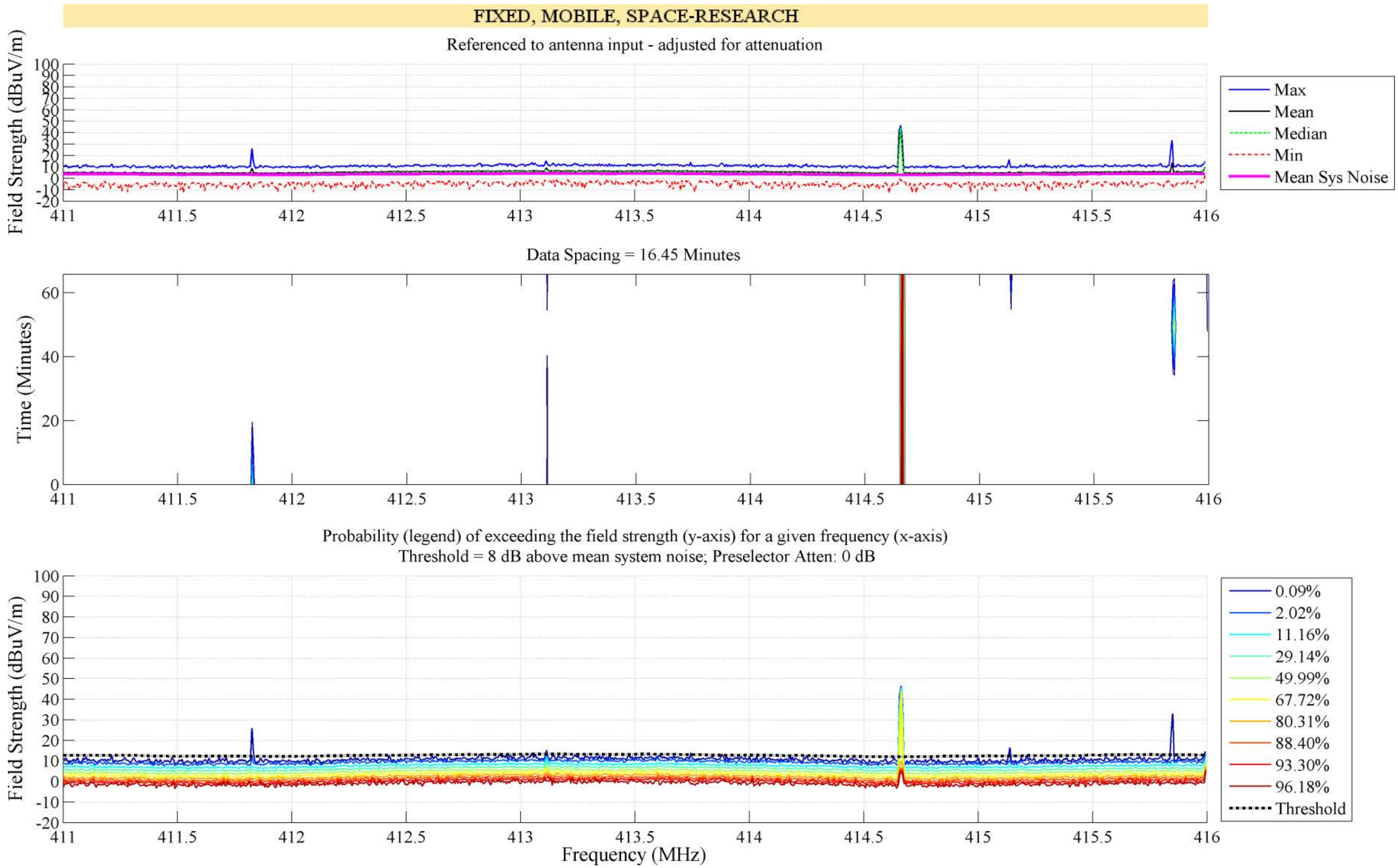

Figure C-15. Static spectrum survey measurements from 411 to 416 MHz processed over a one-hour time slice.

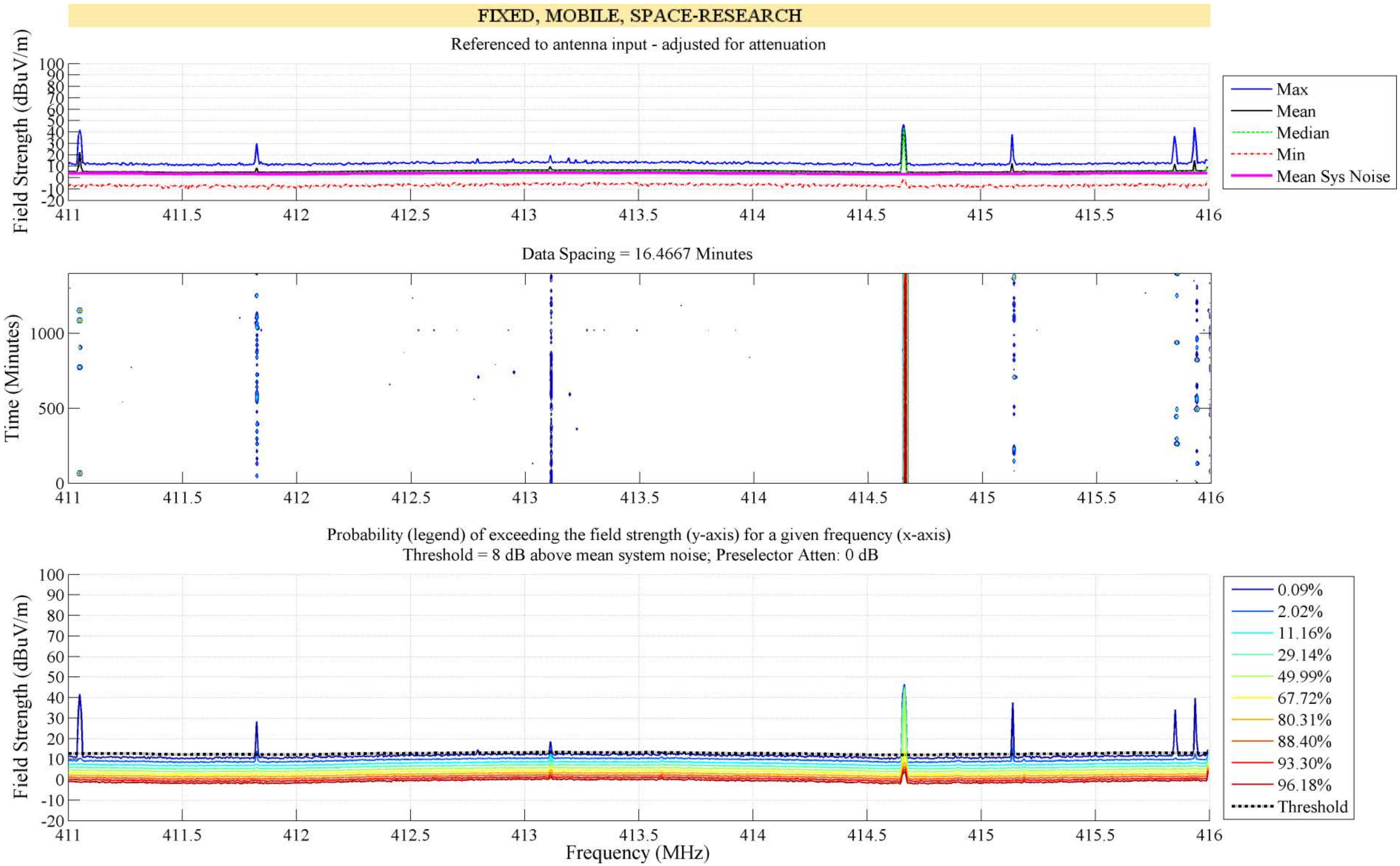

Figure C-16. Static spectrum survey measurements from 411 to 416 MHz processed over a one-day time slice.

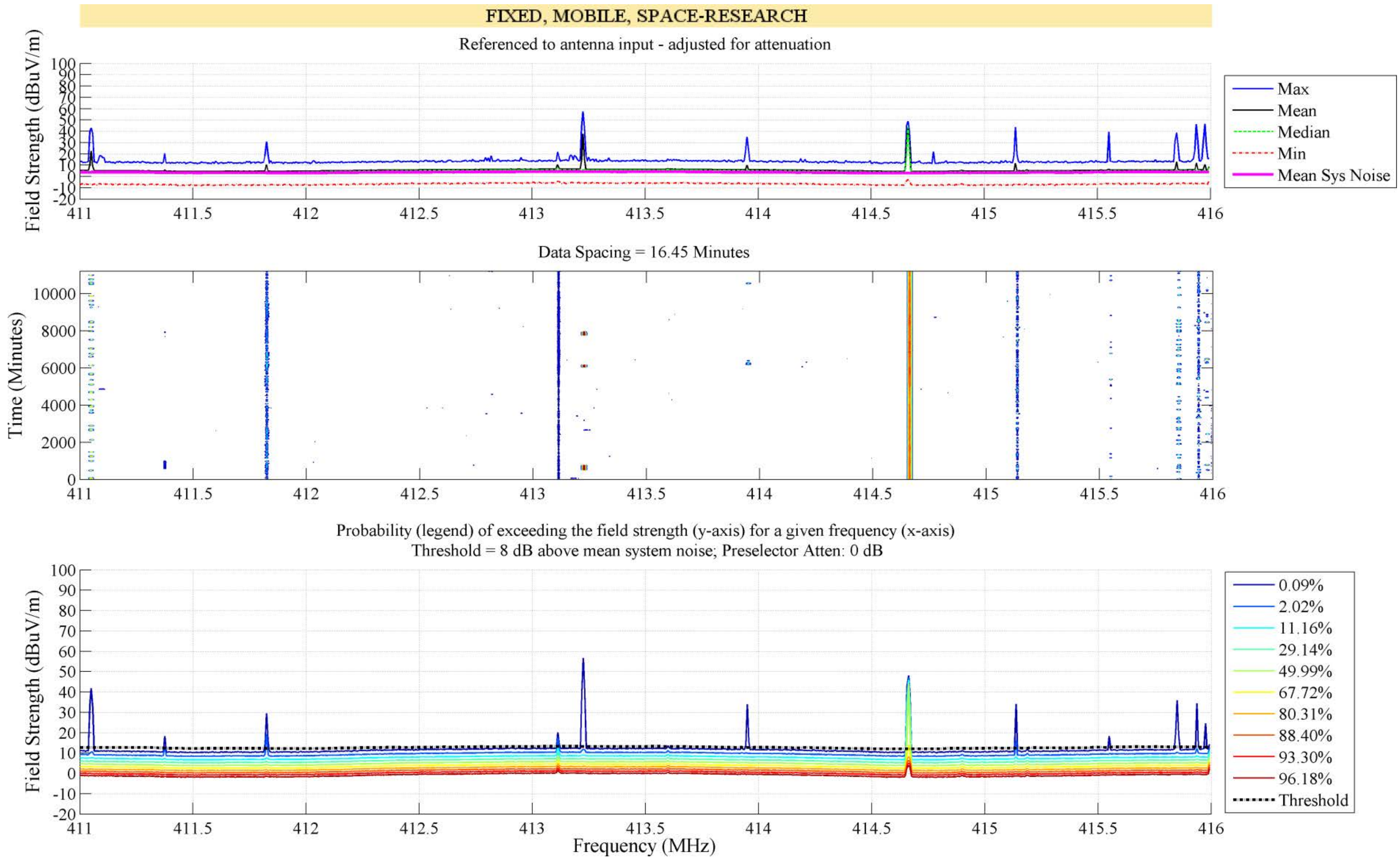

Figure C-17. Static spectrum survey measurements from 411 to 416 MHz processed over a one-week time slice.

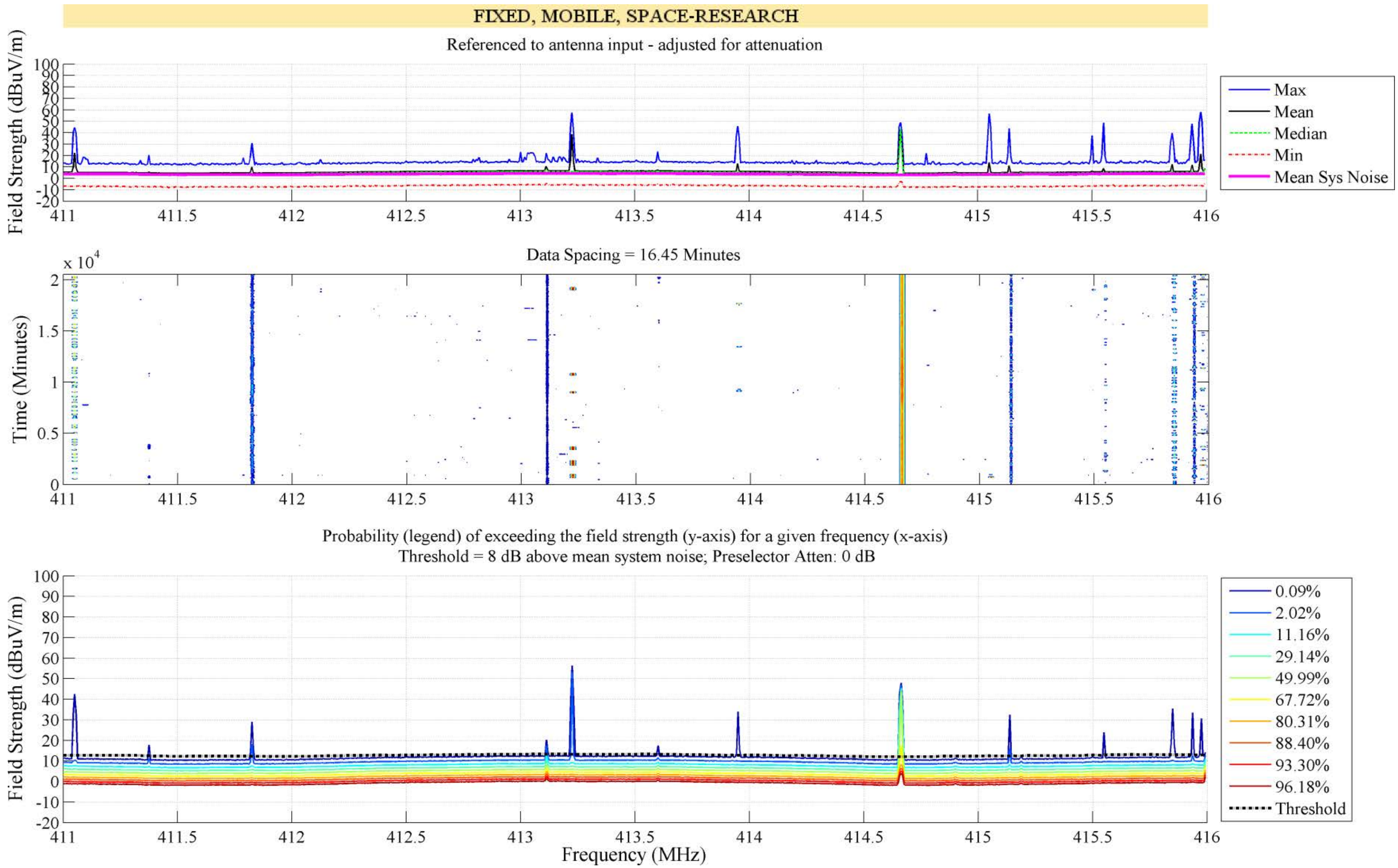

Figure C-18. Static spectrum survey measurements from 411 to 416 MHz processed over a two-week time slice.

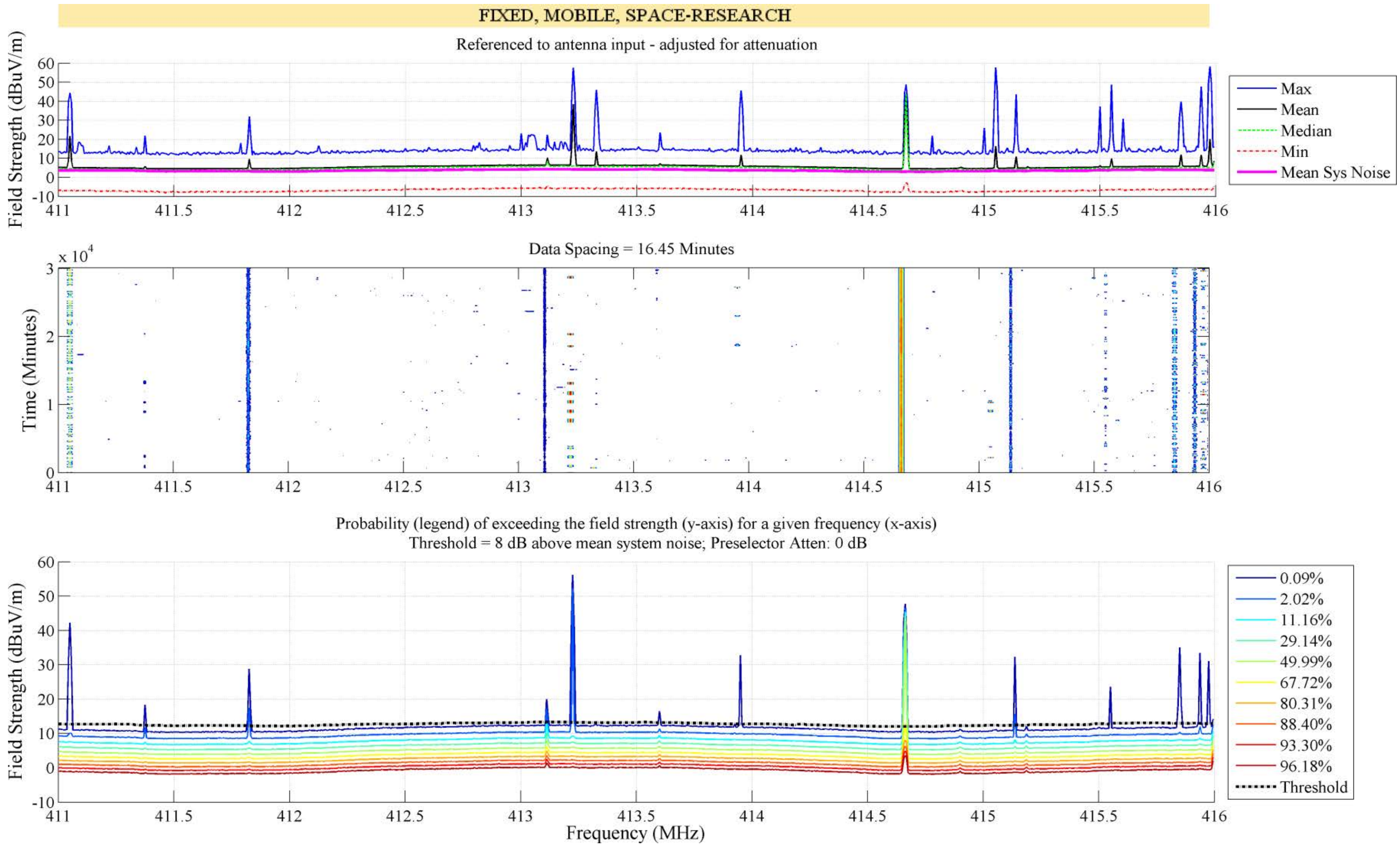

Figure C-19. Static spectrum survey measurements from 411 to 416 MHz processed over a one-month time slice.

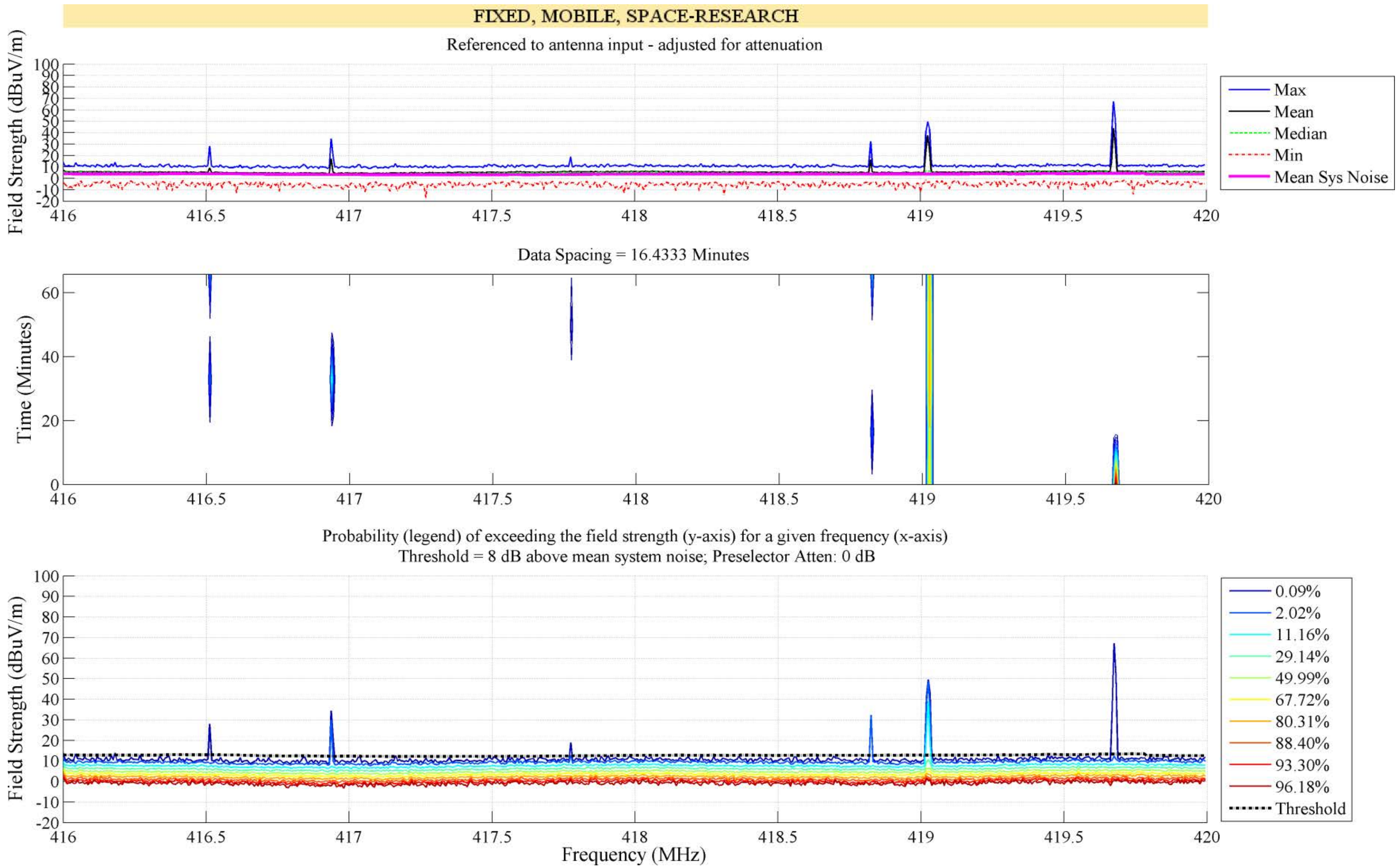

Figure C-20. Static spectrum survey measurements from 416 to 420 MHz processed over a one-hour time slice.

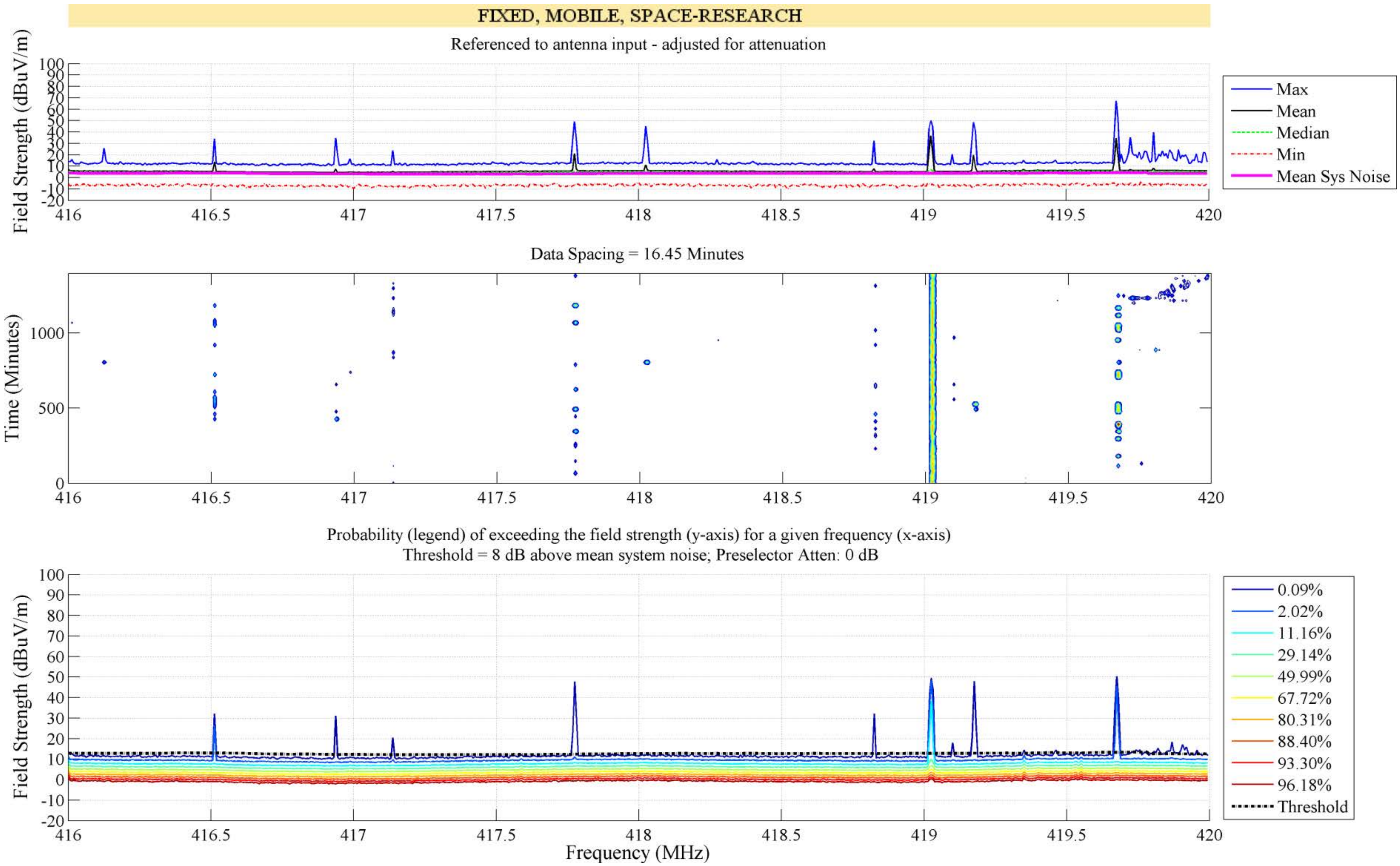

Figure C-21. Static spectrum survey measurements from 416 to 420 MHz processed over a one-day time slice.

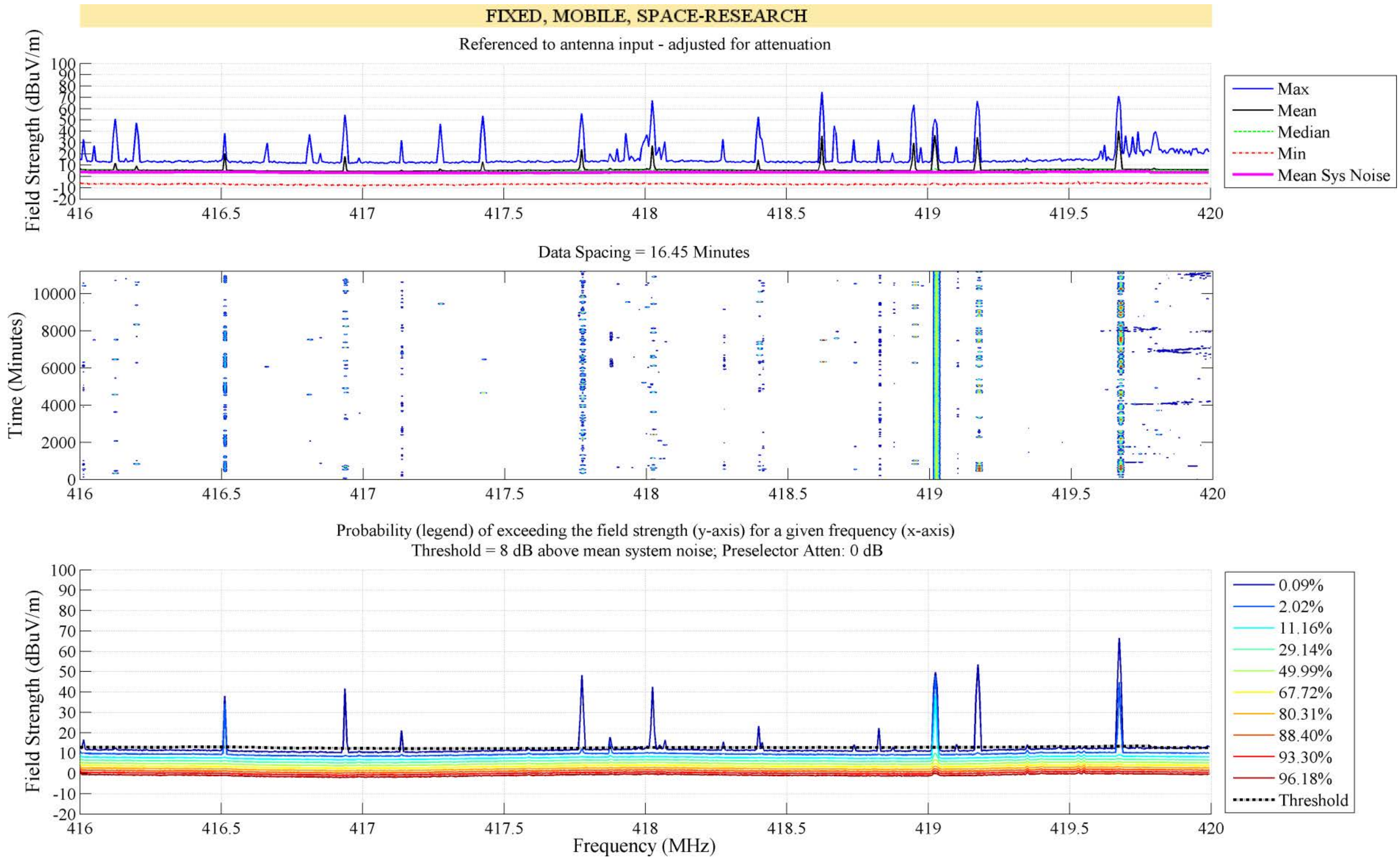

Figure C-22. Static spectrum survey measurements from 416 to 420 MHz processed over a one-week time slice.

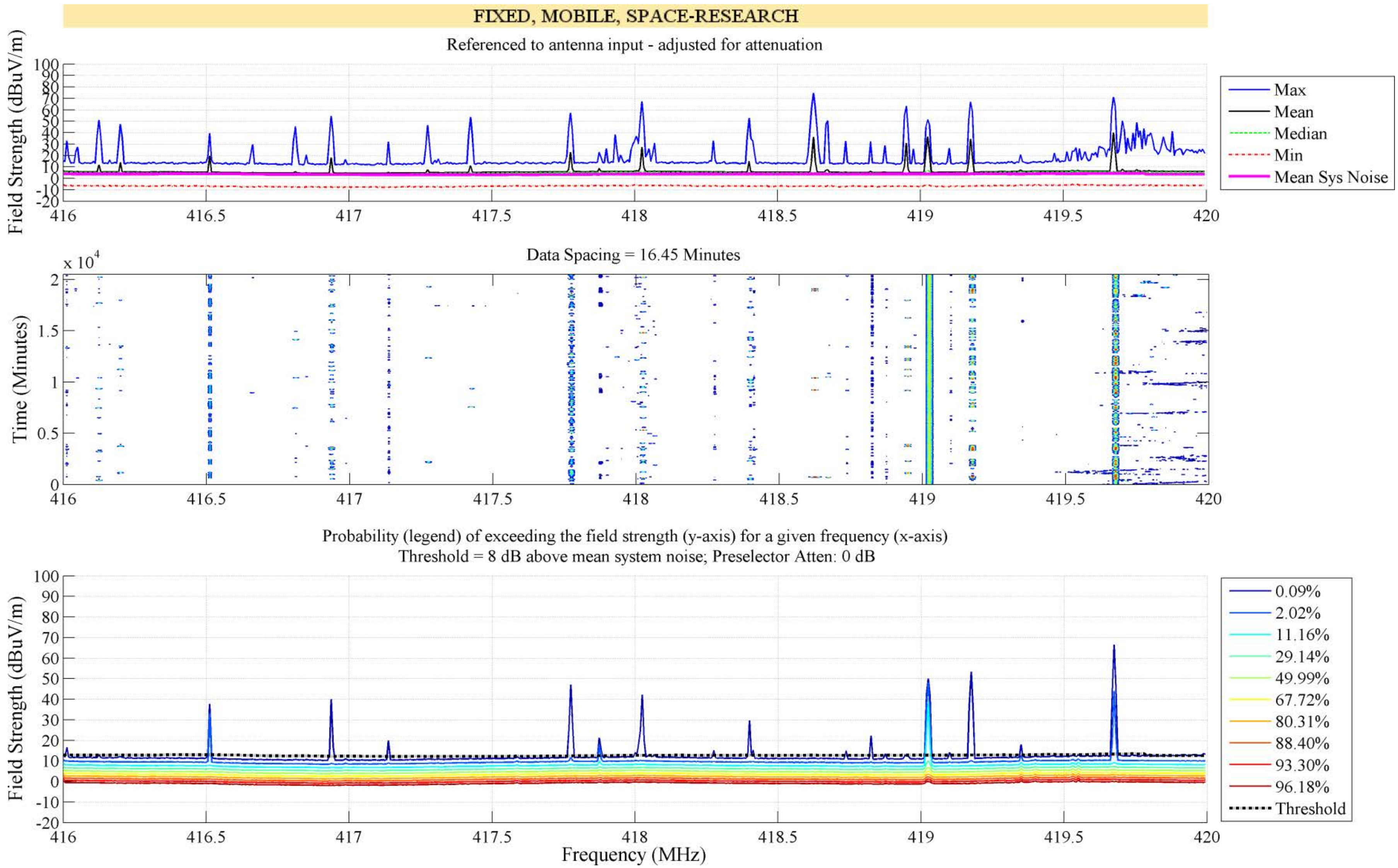

Figure C-23. Static spectrum survey measurements from 416 to 420 MHz processed over a two-week time slice.

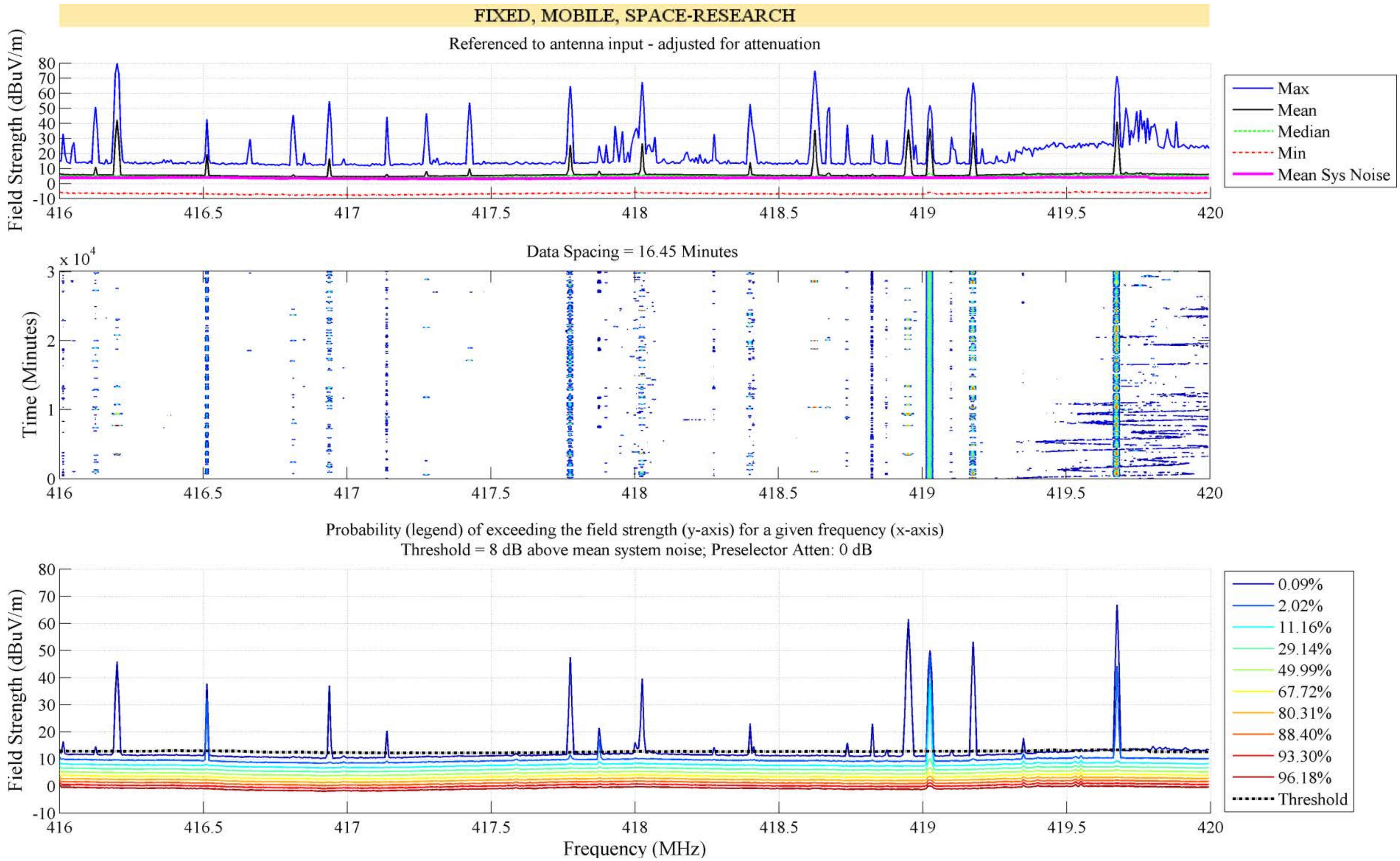

Figure C-24. Static spectrum survey measurements from 416 to 420 MHz processed over a one-month time slice.

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NTIA is responsible for managing the Federal Government's use of the radio spectrum. In discharging this responsibility, NTIA uses the Radio Spectrum Measurement Sciences system to collect spectrum occupancy data for radio frequency assessments. This report shows measured frequency data spanning spectrum from 108 MHz to 10 GHz in the metropolitan area of Denver, Colorado, during the month of June 2011.

16. Key Words (Alphabetical order, separated by semicolons)

land mobile radio (LMR); radar emission spectrum; radio spectrum measurements sciences (RSMS); radio frequency environment; spectrum occupancy; spectrum resource assessment; spectrum survey

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