NTIA Report TR-14-502

Broadband Spectrum Survey in the Chicago, Illinois, Area

Chriss Hammerschmidt

report series

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

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April 2014

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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
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 Communication 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
IIT	Illinois Institute of Technology
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 System
SA	Spectrum Analyzer
SAR	Synthetic Aperture Radar
SARSAT	Search and Rescue Satellite Aided Tracking
SGLS	Space-Ground Link Station
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
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 CHICAGO, ILLINOIS, AREA

Chriss Hammerschmidt[1]

NTIA is responsible for managing the Federal Government's use of the radio spectrum. In discharging this responsibility, NTIA uses the Radio Spectrum Measurement 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 Chicago, Illinois, during a two week period in September 2012.

Keywords: land mobile radio (LMR); radar emission spectrum; radio spectrum measurement system (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's Institute for Telecommunication Sciences (ITS) has been collecting data on radio frequency spectrum utilization. The Radio Spectrum Measurement System (RSMS) 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 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 was conducted on the Illinois Institute of Technology (IIT) campus in the Chicago area in 2012 as part of ongoing research efforts. This is the third in a series of new spectrum survey reports. The first report, published in August 2013, describes occupancy survey results in the Denver area [3]. The second report, published in November 2013, describes occupancy survey results in the San Diego area [4]. The Denver measurements and the San Diego measurements were performed at locations where previous spectrum surveys were conducted [5], [6]. This enables a comparison between current and previous spectrum occupancy measurements. The IIT location provided the opportunity to collect measurements at a location with nearby cellular sites and different terrain than either Denver or San Diego. It also provided an opportunity to compare our methods and results with those of IIT's ongoing spectrum measurement research program [7]. The final location chosen was at the Table Mountain research site near Boulder, Colorado. A report on this measurement is being prepared for publication. The Table Mountain location was chosen because this is ITS' research site and we wanted to investigate current signal levels.

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 radio 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 Chicago, IL 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 processing steps for the graphs shown in Section 3 at frequencies below 500 MHz.

2 MEASUREMENTS IN THE CHICAGO METROPOLITAN AREA

2.1 General Site Selection

The characteristics (i.e., terrain, population density) of the area chosen for a spectrum survey will affect measured spectrum occupancy. For example, measurements taken in a metropolitan area, such as Denver, CO, [3], [5] or Los Angeles, CA, [8] 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 [4], [6] or San Francisco [9], with major naval installations, will show higher levels of usage in bands supporting those operations. We attempt to choose locations that provide the greatest opportunity to measure emissions from the following sources:

- 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.

The location of the 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 [11], 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 Chicago Area Measurement Site Description

The selected measurement site reported here is in Chicago, IL. The measurement location is shown in Figure 1 and the latitude and longitude are 41°50′14.91″ N and 87°37′45.84″ W. The elevation at this location is 182 meters above mean sea level (MSL). The site is located about 5 km south of downtown Chicago and approximately 3.3 km southwest of Northerly Island. The

RSMS-4 truck was parked on the IIT campus. A number of TV station transmitting antennas are located atop the Willis (Sears) Tower about 4.7 km to the northwest of the measurement site.

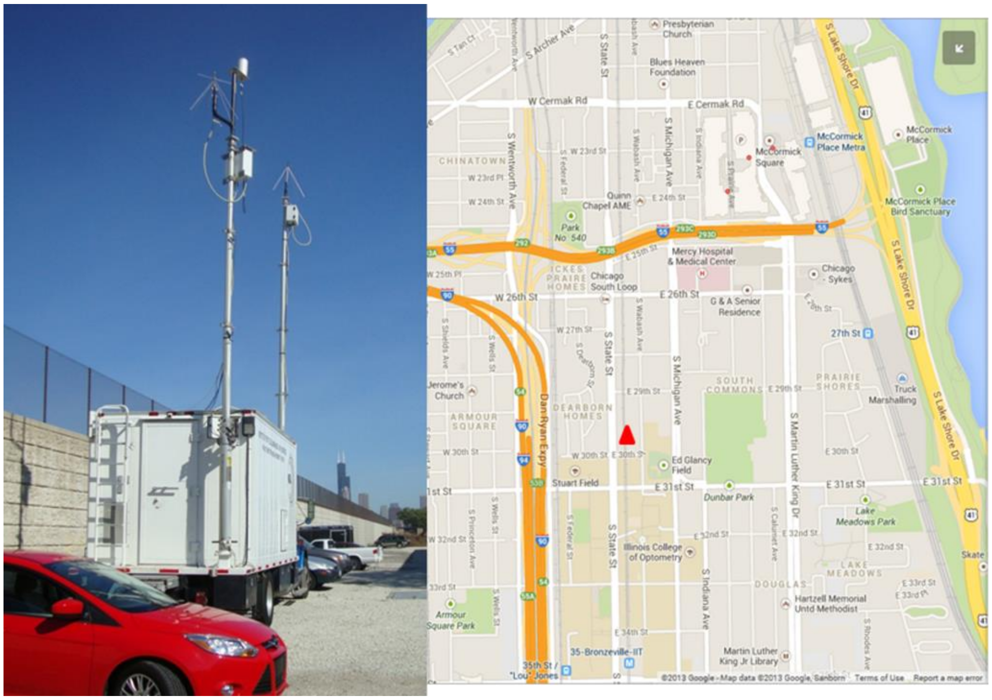

Figure 1. Google® map showing the Chicago area and the RSMS truck at the measurement location. The red triangle marks the measurement location.

The terrain in the Chicago area is the result of mostly glacial processes and is therefore dominated by sedimentary deposits [10]. There is a 182 meter elevation difference between the shores of Lake Michigan and the hills located at the state line between Wisconsin and Illinois. Prominent physical features in the area include Lake Michigan, the Chicago Harbor, and Northerly Island. The dominant sediment is clayey till above bedrock composed of dolomite. An elevation profile of this area is shown in Figure 2. Because this area is relatively flat, it is conducive to the propagation of radio signals. The major obstacles in the vicinity are the buildings in and around downtown Chicago.

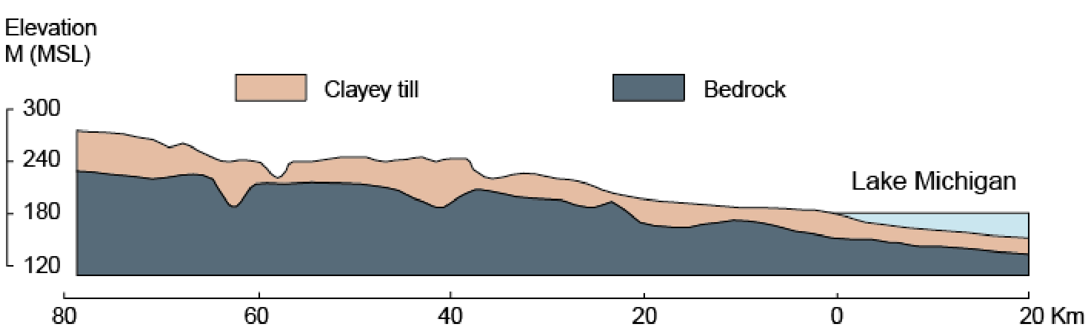

Figure adapted from M. J. Chrzastowski, "Chicagoland, Geology and the Making of a Metropolis," Field Excursion for the 2005 Annual Meeting of the Association of American State Geologists, June 2005, p. 6.

Figure 2. Elevation Profile for the Chicago area.

The RSMS truck was located near one of the IIT buildings and adjacent to the tracks of the Chicago Transit Authority Red Line. Chicago O'Hare Airport is located approximately 27.5 km to the northwest and Chicago Midway Airport lies to the southwest at a distance of 12 km. During the tests, the antenna masts were raised approximately 10 m (30 ft.) to get as unobstructed a view of the surrounding area as possible.

The site was in close proximity to I-94 and to cellular sites located on or near the IIT campus. There are television transmitters within 5 km of the measurement location in the downtown area. U.S. Cellular field (fka Comiskey Park) is located within 1 km of the measurement site. A fire station was located less than a kilometer from the site and several police stations were within 4 km.

2.3 Measurement System Description

The spectrum survey was conducted from September 9, 2012 to September 22, 2012. 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. The measurement schedule was adjusted to obtain a maximal number 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 types of signal(s) 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 were used. The schematics for both systems are shown in Figure 3. The first system, the LMR system, measures only 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 was 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 were not conducted during this survey and no data was taken in the radar altimeter band from 4200 to 4400 MHz due to time constraints.

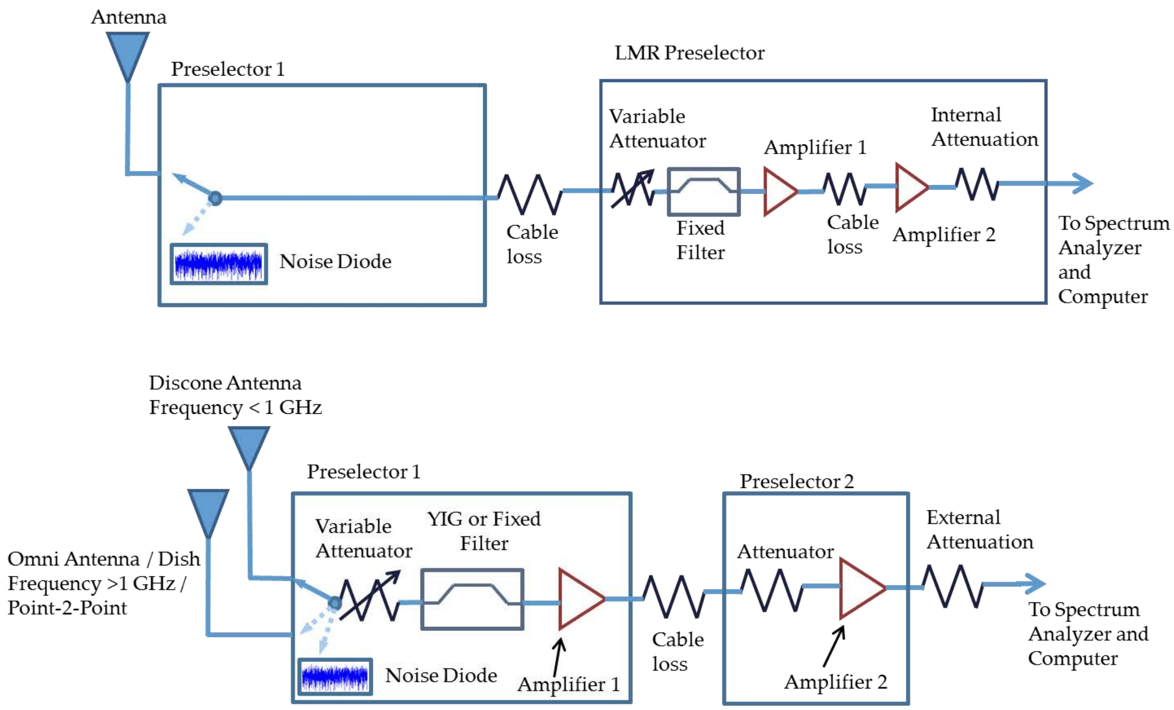

Figure 3. System schematic for the LMR system and the broad-frequency system.

The preselector/preamplifier unit, schematically depicted in Figure 3, serves to extend the dynamic range, improve measurement system sensitivity, and reduce 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. Radio frequency (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 increase the signal above 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.

Three tailored algorithms are used for these measurements: 1) a time-domain acquisition with fast Fourier transform (FFT) processing algorithm (TDwFFT), 2) a swept-spectrum measurement algorithm (Swept), and 3) a stepped-spectrum measurement algorithm (Stepped). 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.

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 measurement period. These bands were measured approximately 1200 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 [6].

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 shows the type of measurement, the frequency range(s), and the measurement algorithm used. This description is directly related to the measurement filename; 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 the 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 show they are fixed in frequency and possibly only vary in output power during the day and at night. Radar bands were measured every 33 hours since some radars are prevalent in the area and others are not. This interval also ensured that we measured some radars in the evening to observe diurnal 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[2]_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

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

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

Event	Description of Measurement (type; frequencies; algorithm)	How measurement is repeated	Minimum Hours Between	Total Times Measured
1	Calibration; 116–138_225–406_420–476 MHz; TDwFFT	Repeat Ongoing	54	4
2	Measurement; 116–138_225–406_420–476 MHz; TDwFFT	Repeat Ongoing	0	21
3	Calibration; TV_174–216_476–500 MHz; TDwFFT	Repeat 10x	46	5
4	Measurement; TV_174–216_476–500 MHz; TDwFFT	Repeat 10x	30	5
5	Calibration; TV_500–608_614–763 MHz; Swept	Repeat 10x	46	5
6	Measurement; TV_500–608_614–763 MHz; Swept	Repeat 10x	30	7
7	Calibration; TVWS_180–210 MHz; TDwFFT	Repeat 2x	200	2
8	Measurement; TVWS_180–210 MHz; TDwFFT	Repeat 2x	200	2
9	Calibration; TVWS_500–608_614–763 MHz; Swept	Repeat 2x	200	2
10	Measurement; TVWS_500–608_614–763 MHz; Swept	Repeat 2x	200	2
11	Calibration; Radar_420–450 MHz; Stepped	Repeat Ongoing	54	5
12	Measurement; Radar_420–450 MHz; Stepped	Repeat Ongoing	33	7
13	Calibration; Cellular_Misc_763–1000 MHz; Swept	Repeat Ongoing	46	5
14	Measurement; Cellular_Misc_763–1000 MHz; Swept	Repeat Ongoing	0	22
15	Calibration; Radar_902–928 MHz; Stepped	Repeat Ongoing	54	5
16	Measurement; Radar_902–928 MHz; Stepped	Repeat Ongoing	33	7
17	Calibration; Narrowband_1000–2000 MHz; Swept	Repeat Ongoing	46	5
18	Measurement; Narrowband_1000–2000 MHz; Swept	Repeat Ongoing	0	21
19	Calibration; Radar_1215–1400 MHz; Stepped	Repeat Ongoing	54	4
20	Measurement; Radar_1215–1400 MHz; Stepped	Repeat Ongoing	33	7
21	Calibration; Narrow_2000–2700 MHz; Swept	Repeat Ongoing	46	5
22	Measurement; Narrow_2000–2700 MHz; Swept	Repeat Ongoing	0	21
23	Calibration; Radar_2700–2900 MHz; Stepped	Repeat Ongoing	54	5
24	Measurement; Radar_2700–2900 MHz; Stepped	Repeat Ongoing	33	7
25	Calibration; Radar_2900–3650 MHz; Stepped	Repeat Ongoing	54	5
26	Measurement; Radar_2900–3650 MHz; Stepped	Repeat Ongoing	33	6
27	Calibration; Narrowband_2900–4200 MHz; Swept	Repeat Ongoing	46	5
28	Measurement; Narrowband_2900–4200 MHz; Swept	Repeat Ongoing	0	22
29	Calibration; Radar_5250–5925 MHz; Stepped	Repeat Ongoing	54	5
30	Measurement; Radar_5250–5925 MHz; Stepped	Repeat Ongoing	33	6
31	Calibration; Misc_4400–5000 MHz; Swept	Repeat Ongoing	46	5
32	Measurement; Misc_4400–5000 MHz; Swept	Repeat Ongoing	0	20
33	Calibration; Misc_5000–7000 MHz; Swept	Repeat Ongoing	46	5
34	Measurement; Misc_5000–7000 MHz; Swept	Repeat Ongoing	0	20
35	Calibration; Misc_7000–8000 MHz; Swept	Repeat Ongoing	46	5
36	Measurement; Misc_7000–8000 MHz; Swept	Repeat Ongoing	0	20
37	Calibration; Misc_8000–9000 MHz; Swept	Repeat Ongoing	46	5

Event	Description of Measurement (type; frequencies; algorithm)	How measurement is repeated	Minimum Hours Between	Total Times Measured
38	Measurement; Misc_8000–9000 MHz; Swept	Repeat Ongoing	0	20
39	Calibration; Misc_9000–10000 MHz; Swept	Repeat Ongoing	46	5
40	Measurement; Misc_9000–10000 MHz; Swept	Repeat Ongoing	0	21
41	Calibration; Radar_8500–10000 MHz; Stepped	Repeat Ongoing	54	5
42	Measurement; Radar_8500–10000 MHz; Stepped	Repeat Ongoing	33	6

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 and stepped algorithms have similar parameters because they used 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. Sample events for measurement algorithms.

Parameter	Swept	Stepped
RBW (MHz)	0.3	1.0
VBW (MHz)	0.3	1.0
Start Frequency (MHz)	4400	2900
Stop Frequency (MHz)	5000	3650
Sweep Time (ms)	1000	12000
Points/Trace	2001	8192
Preselector Antenna Ports	2-1	2-1
Detector Type	Average	Positive Peak
Filter Type	Fixed	Fixed or Tunable
Preselector Attenuation (dB)	0	Auto
Sweeps/Event	100	751
Step size (MHz)		1

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 is completed, 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 [12] 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 two presentations of data in this report. Swept-spectrum and TDwFFT data are shown using three graphs and stepped-spectrum measurements are shown using two graphs. A brief description of the graphs is given here; however, more detailed information on the actual algorithms is given in Appendix A of [3] or [4].

When three graphs are shown on a page, as shown in Figure 4, 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 [5], [6], [8], [9] 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 field-strength on the y-axis 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 above mean system noise)**
108 – 112	9
112 – 116	13
116 – 132	18
132 – 138	16
138 – 143	13
143 – 149	12
149 – 174	9
174 – 216	4
216 – 225	9
225 – 406	8
406 – 420	9
420 – 476	8
476 – 500	4
500 – 4200	6
4400 – 10,000	1

Radar or stepped measurements are shown using two graphs, as shown in Figure 38. 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.

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 see 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 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 Chicago 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 density of frequency 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 previously reported LMR occupancy studies [11], [13] should be performed.

The following figures show results from the spectrum survey. Discussions about each graph follow after 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 [14] and the Federal Spectrum Use Summary [15]. For a complete description of the allocations, the reader is referred to [1], [12], [14], or [15].

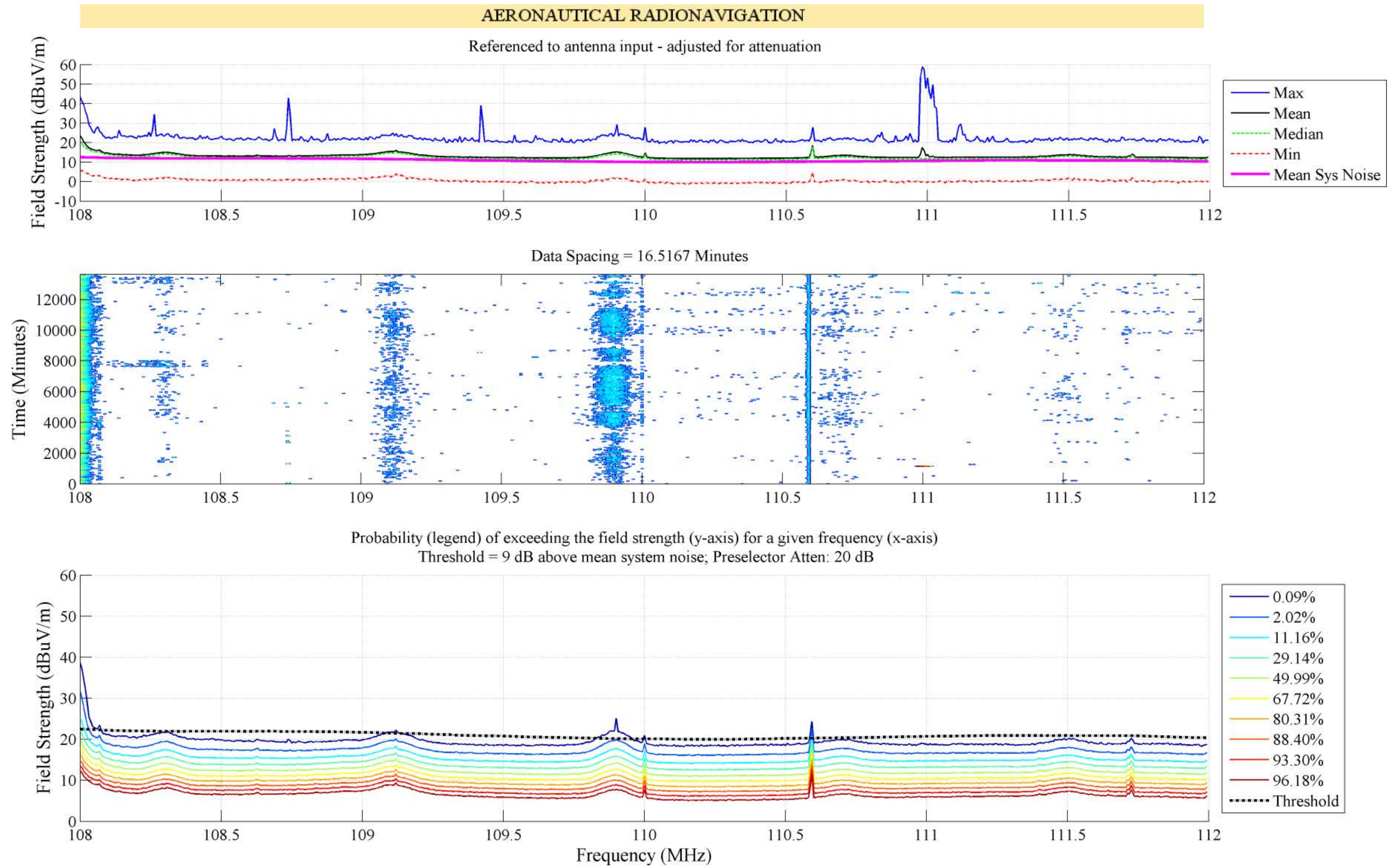

Figure 4. NTIA spectrum survey results from 108 to 112 MHz in Chicago, IL, September 2012.

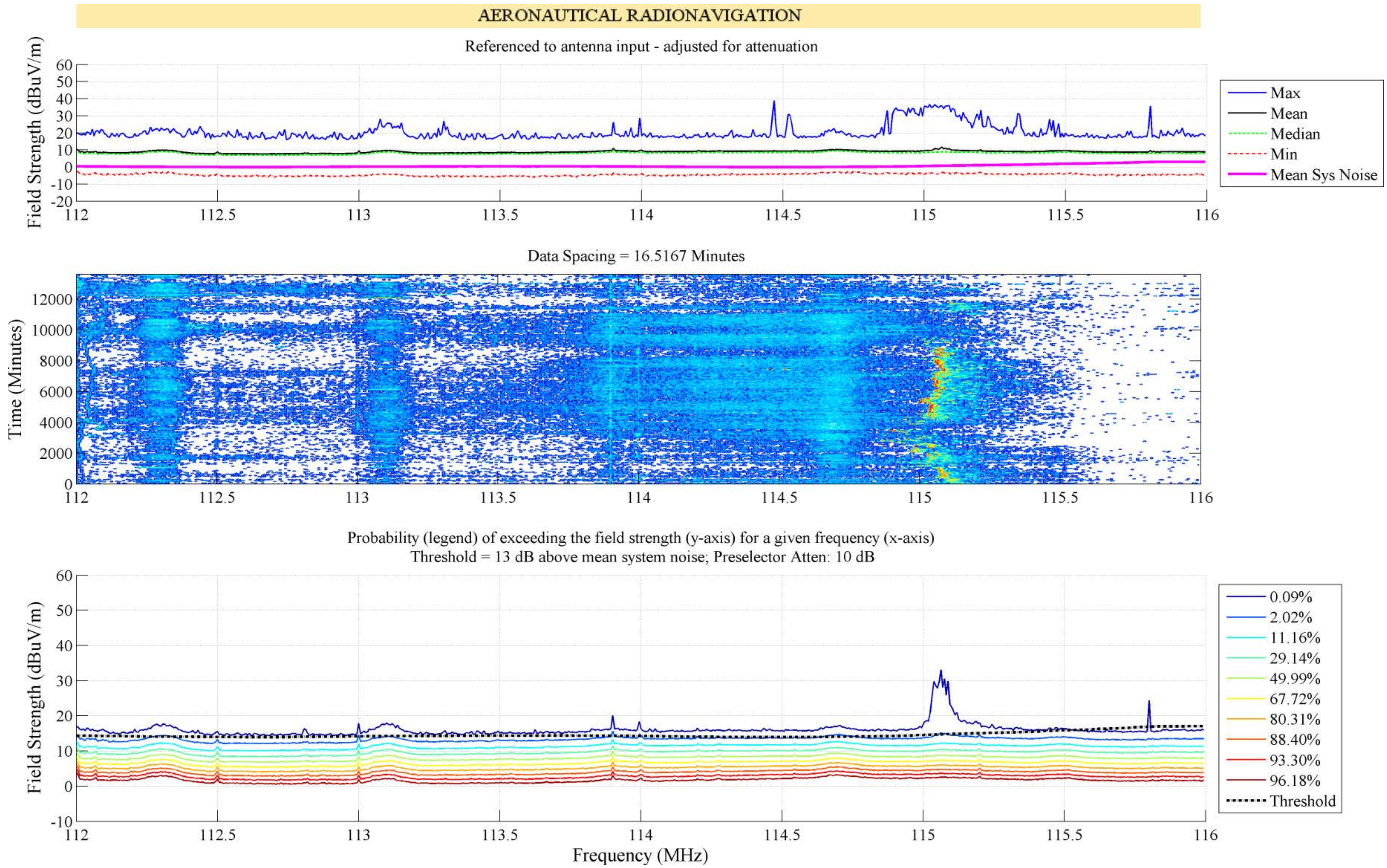

Figure 5. NTIA spectrum survey results from 112 to 116 MHz in Chicago, IL, September 2012.

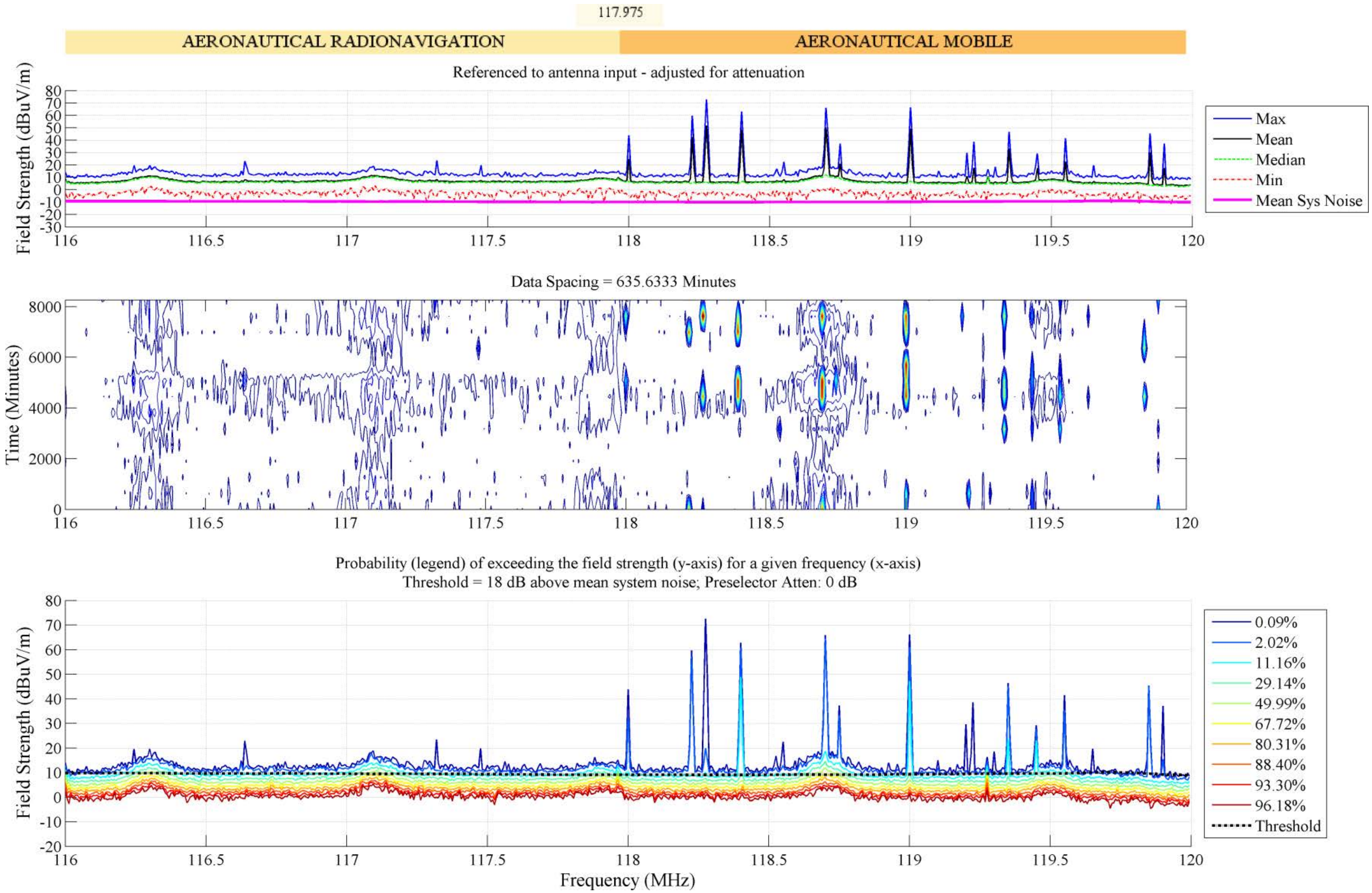

Figure 6. NTIA spectrum survey results from 116 to 120 MHz in Chicago, IL, September 2012.

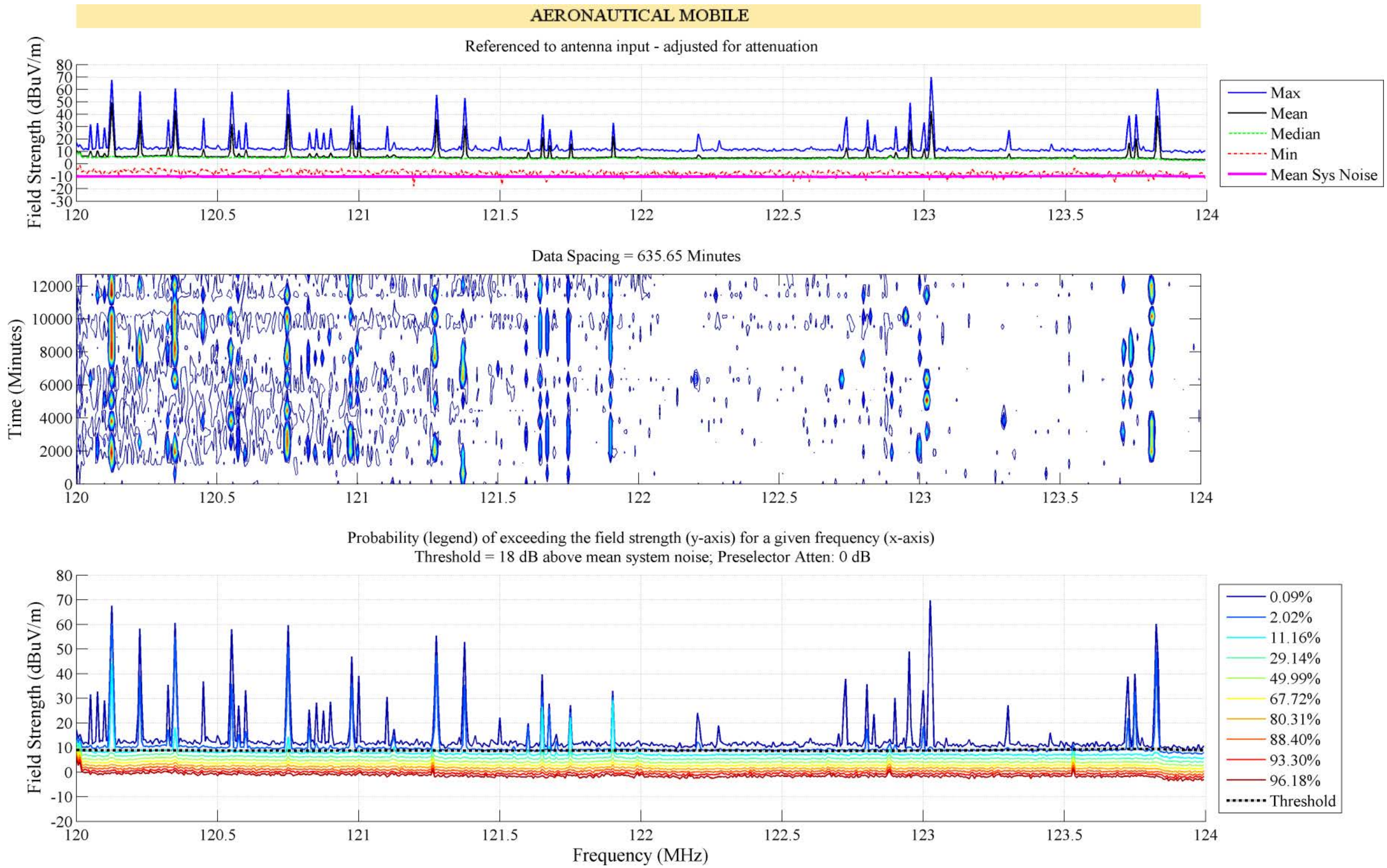

Figure 7. NTIA spectrum survey results from 120 to 124 MHz in Chicago, IL, September 2012.

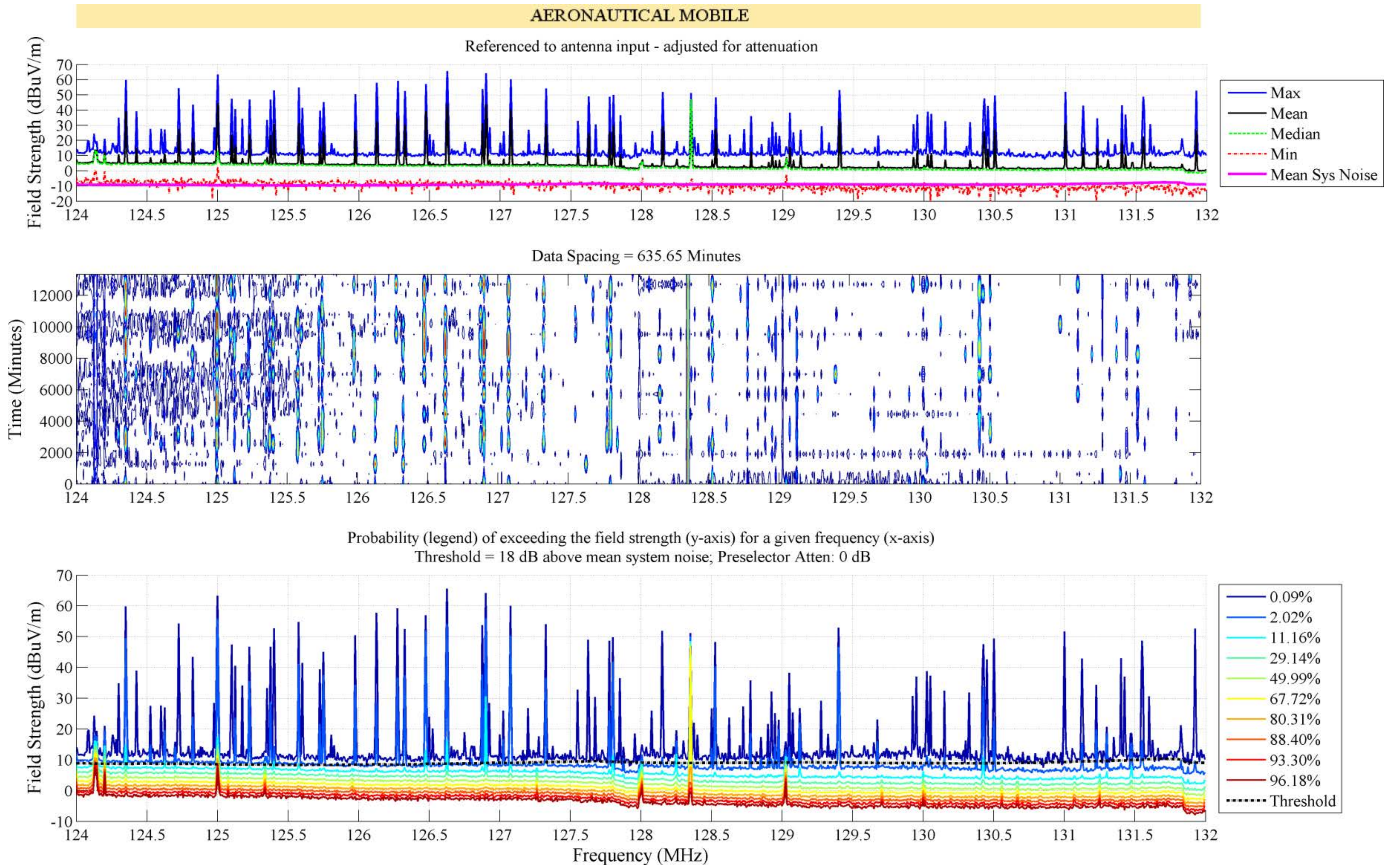

Figure 8. NTIA spectrum survey results from 124 to 132 MHz in Chicago, IL, September 2012.

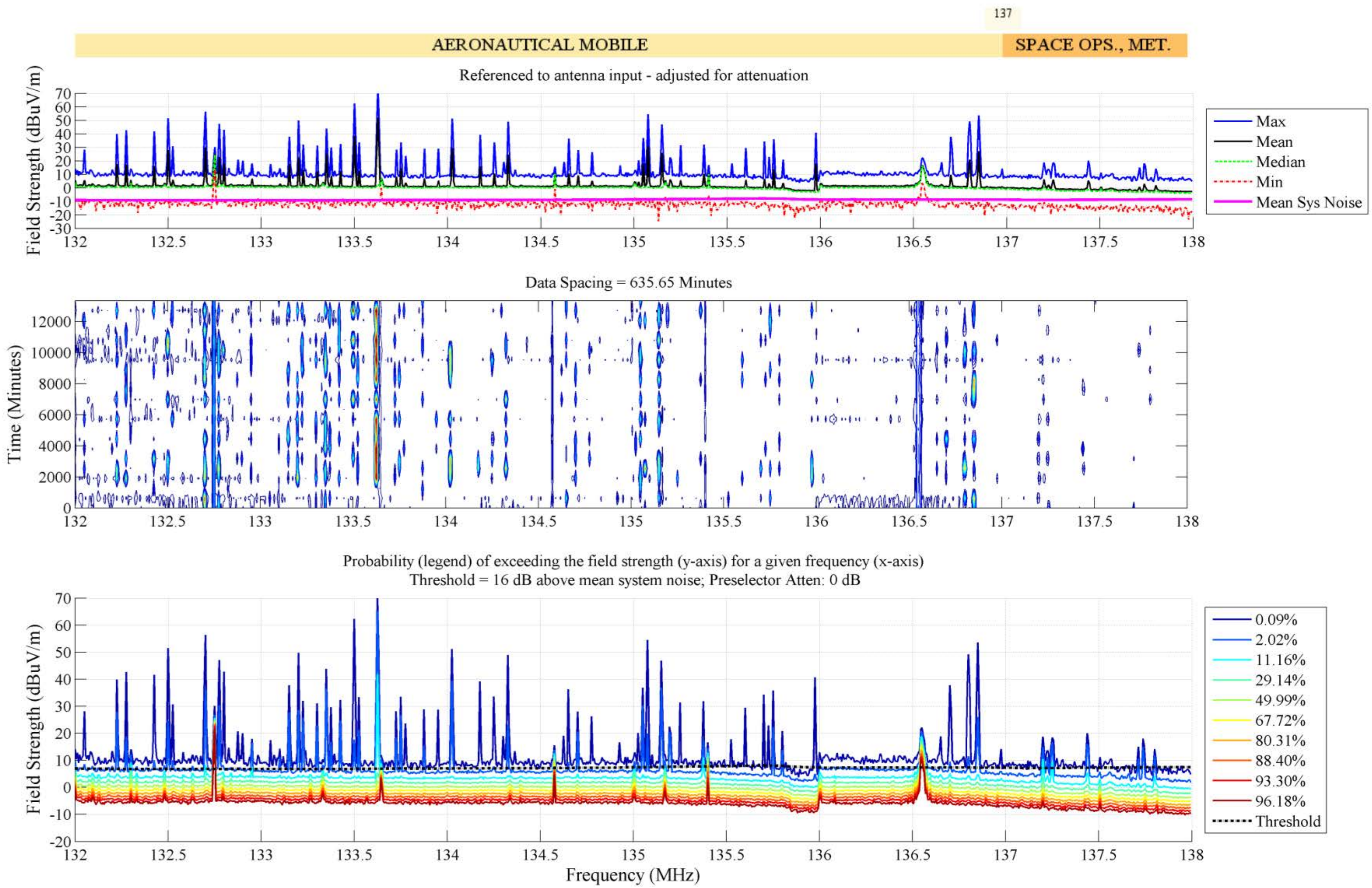

Figure 9. NTIA spectrum survey results from 132 to 138 MHz in Chicago, IL, September 2012.

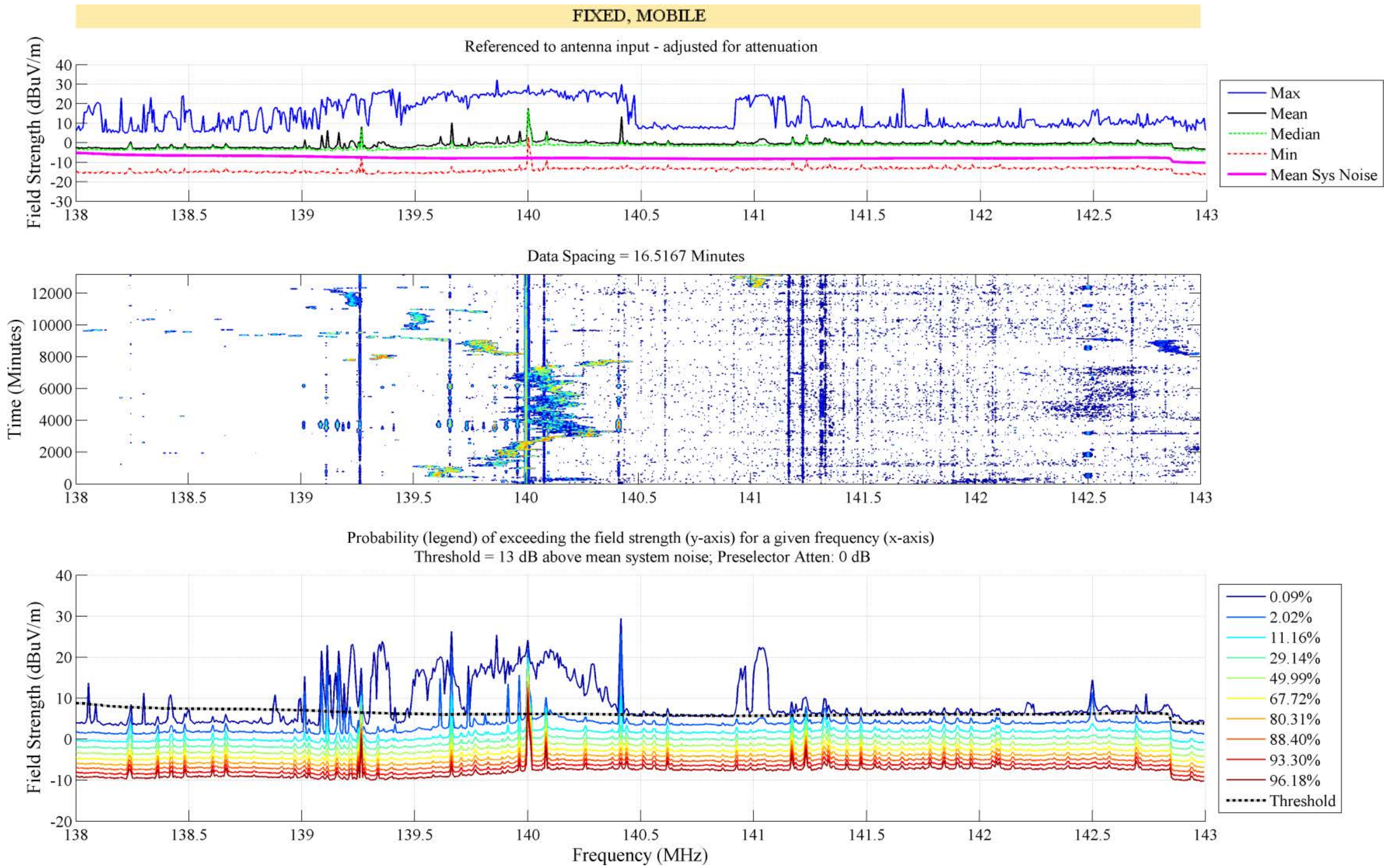

Figure 10. NTIA spectrum survey results from 138 to 143 MHz in Chicago, IL, September 2012.

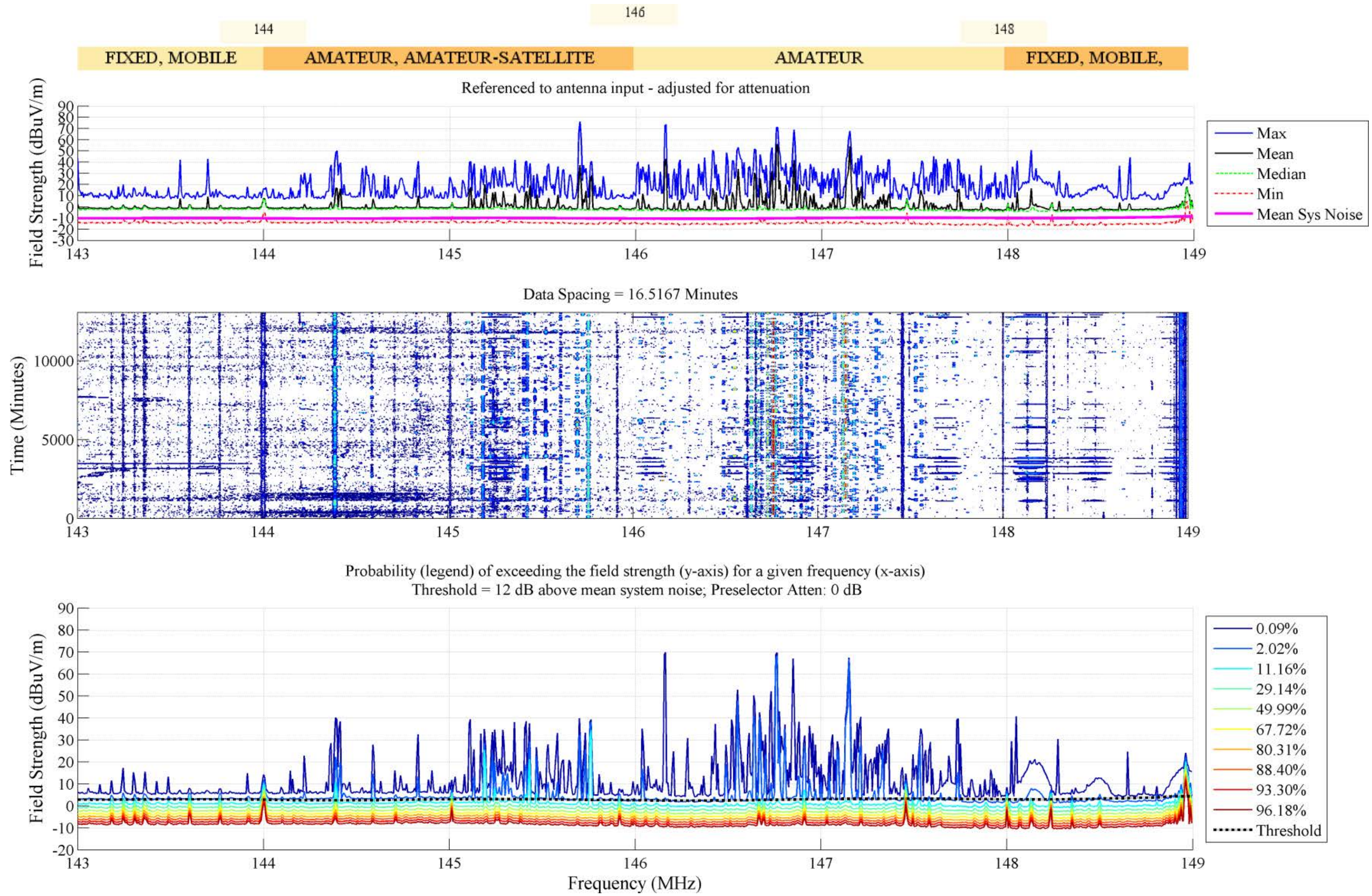

Figure 11. NTIA spectrum survey results from 143 to 149 MHz in Chicago, IL, September 2012.

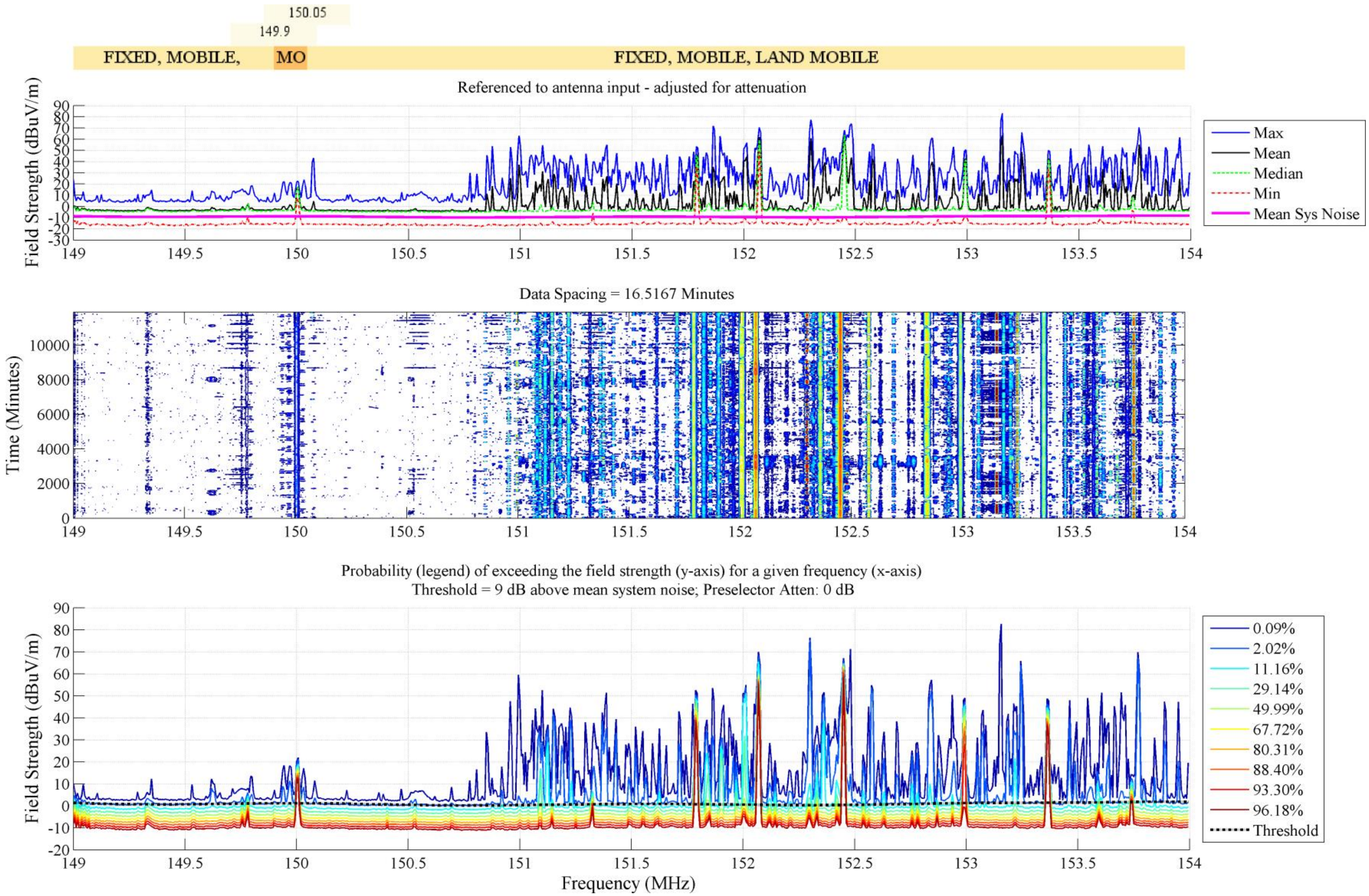

Figure 12. NTIA spectrum survey results from 149 to 154 MHz in Chicago, IL, September 2012.

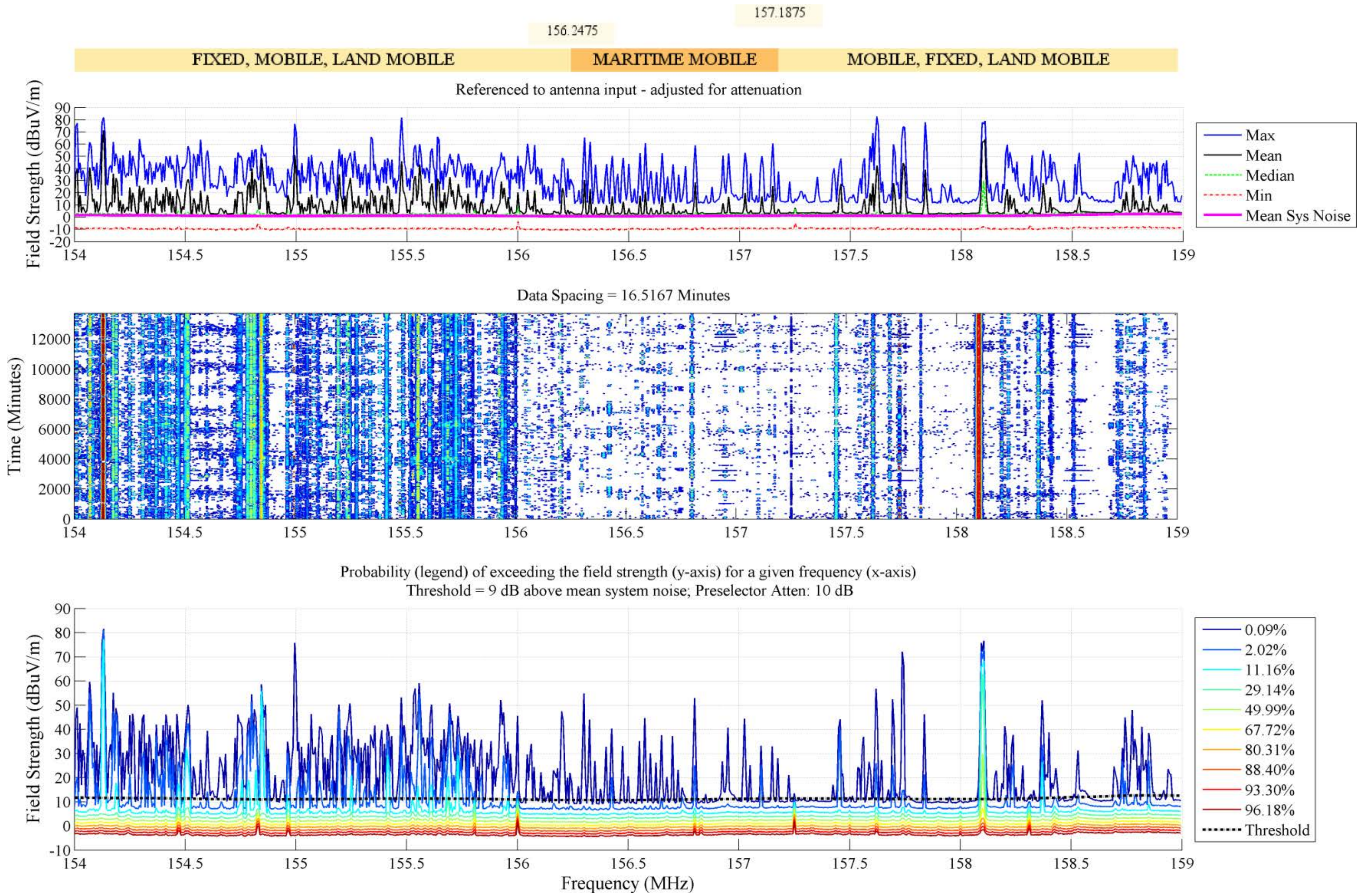

Figure 13. NTIA spectrum survey results from 154 to 159 MHz in Chicago, IL, September 2012.

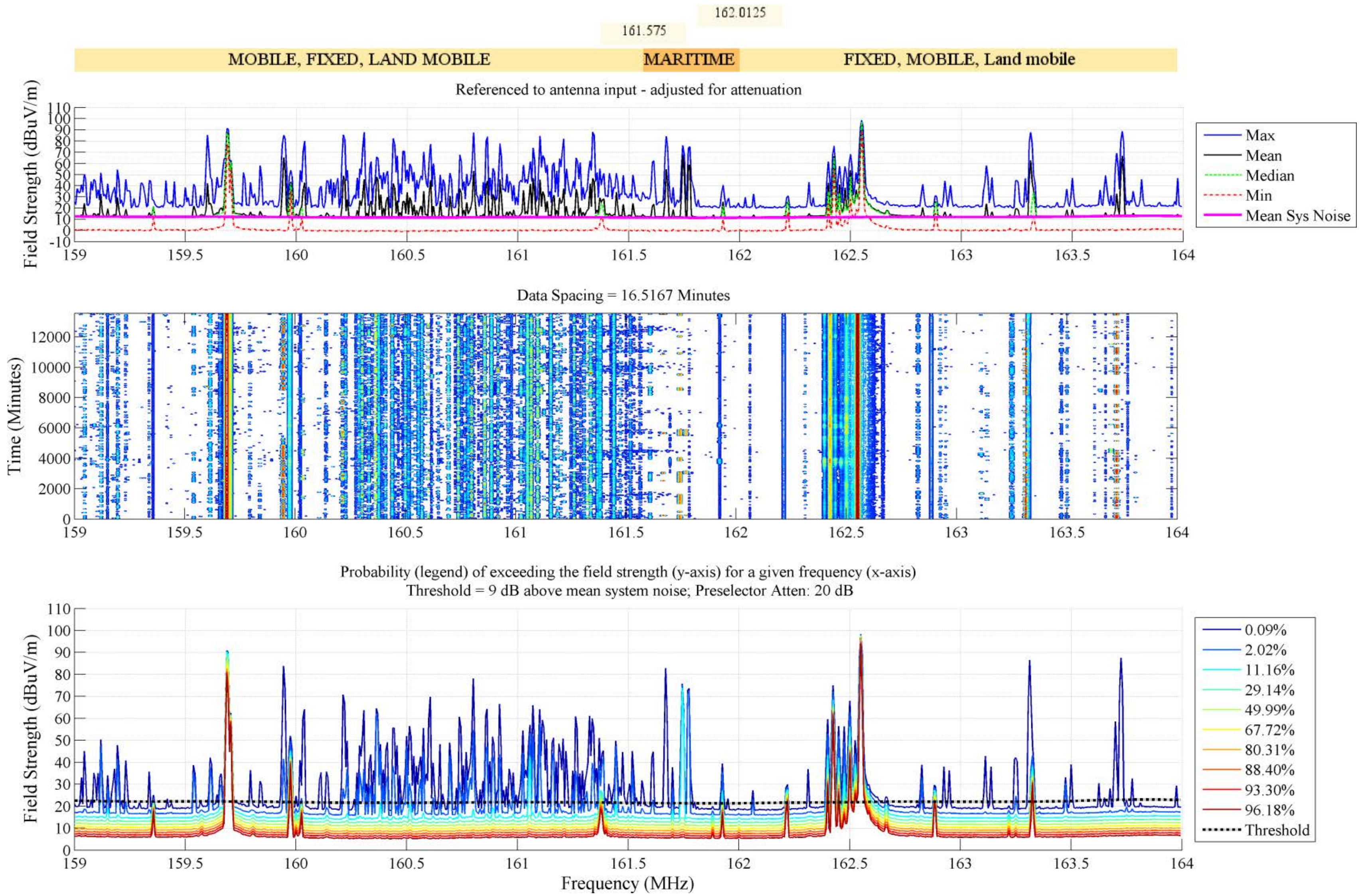

Figure 14. NTIA spectrum survey results from 159 to 164 MHz in Chicago, IL, September 2012.

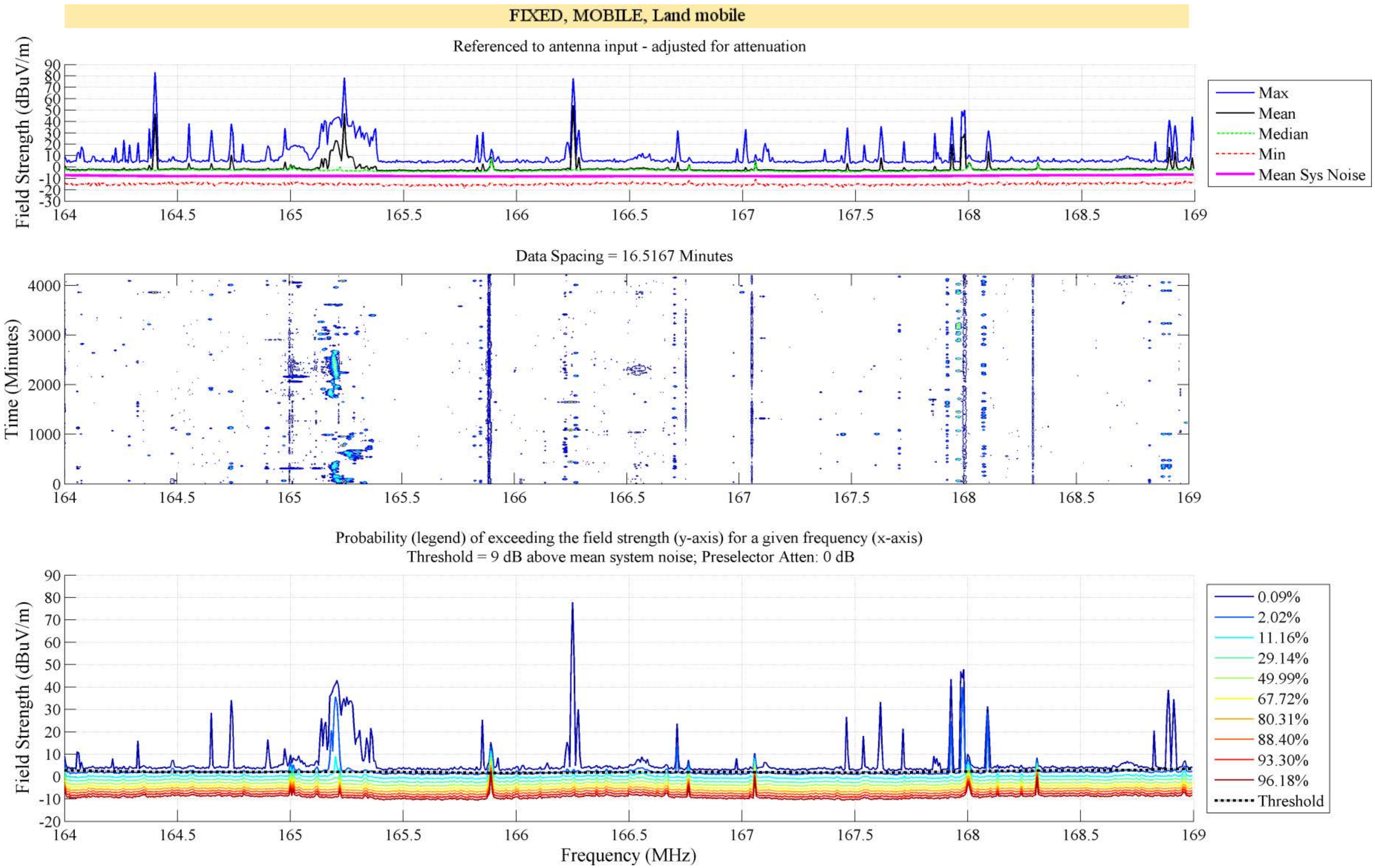

Figure 15. NTIA spectrum survey results from 164 to 169 MHz in Chicago, IL, September 2012.

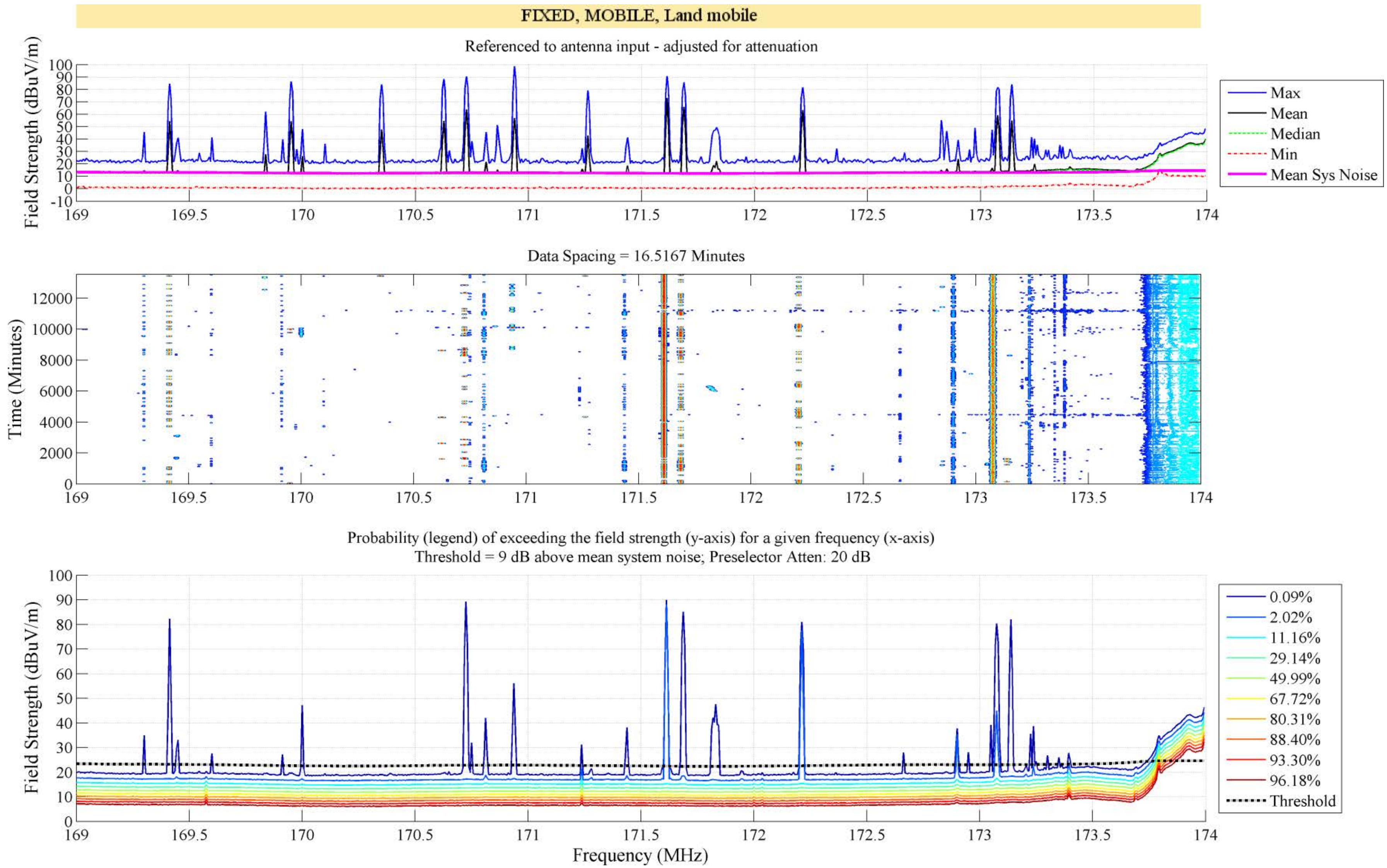

Figure 16. NTIA spectrum survey results from 169 to 174 MHz in Chicago, IL, September 2012.

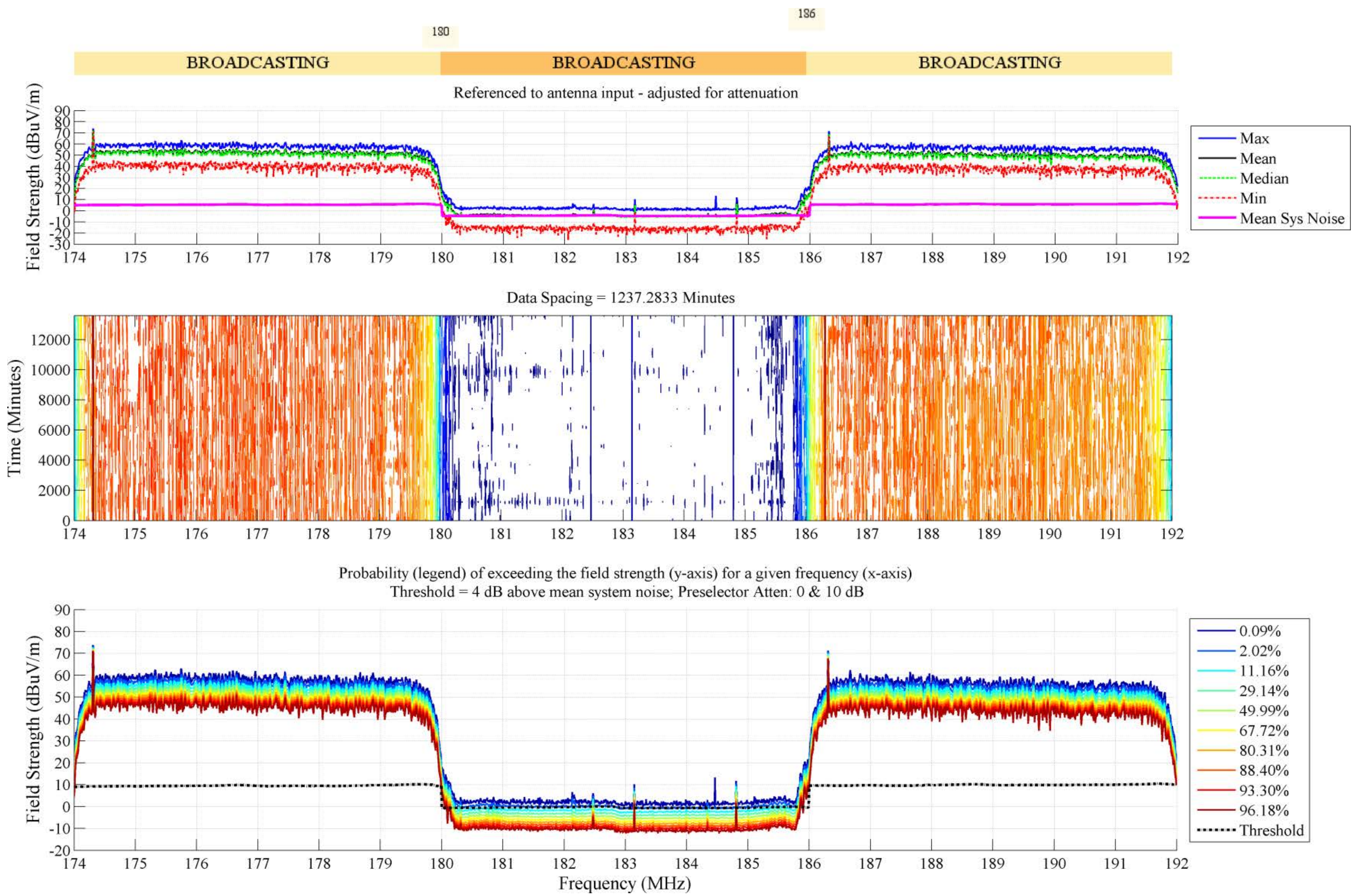

Figure 17. NTIA spectrum survey results from 174 to 192 MHz in Chicago, IL, September 2012.

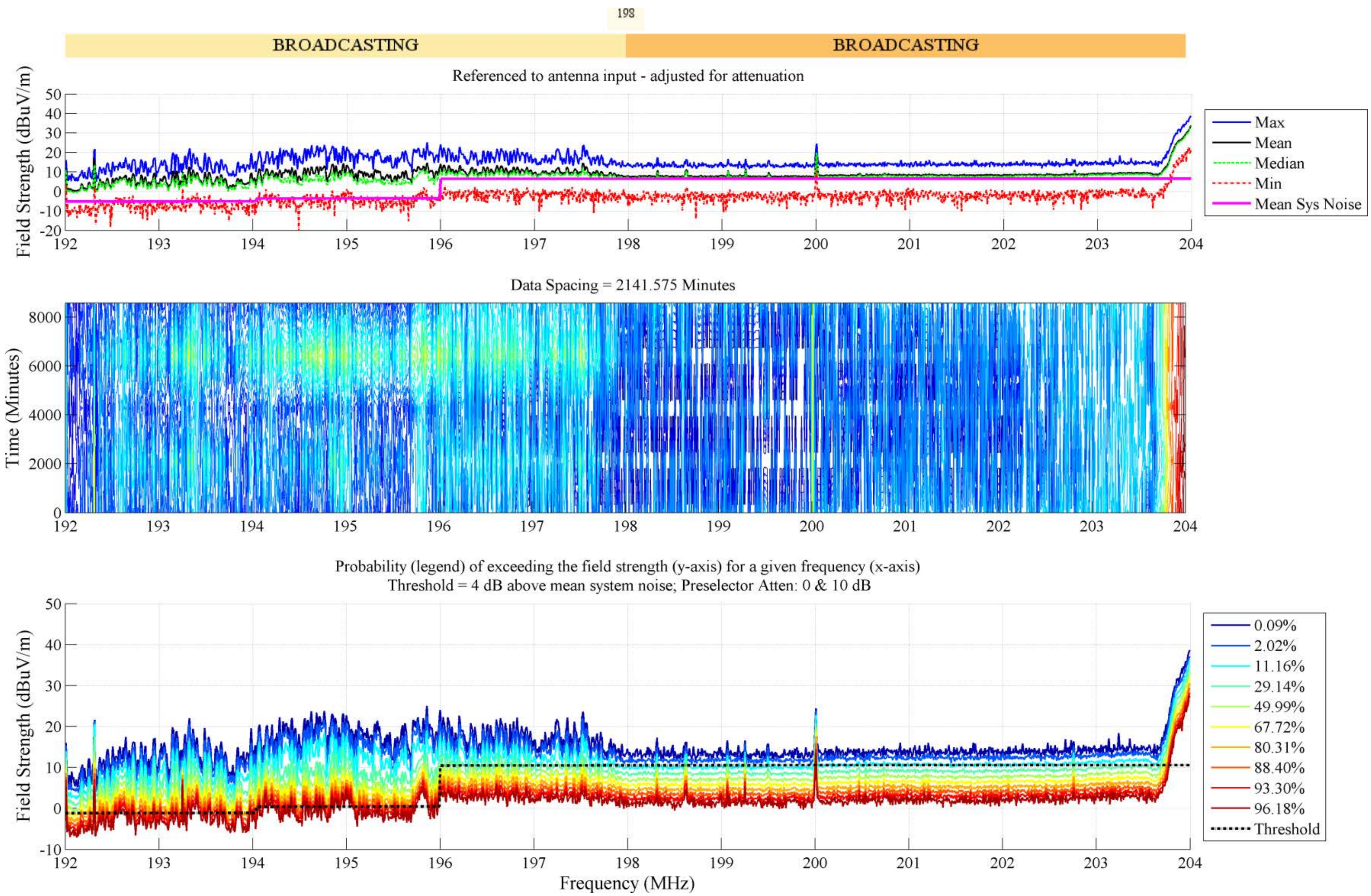

Figure 18. NTIA spectrum survey results from 192 to 204 MHz in Chicago, IL, September 2012.

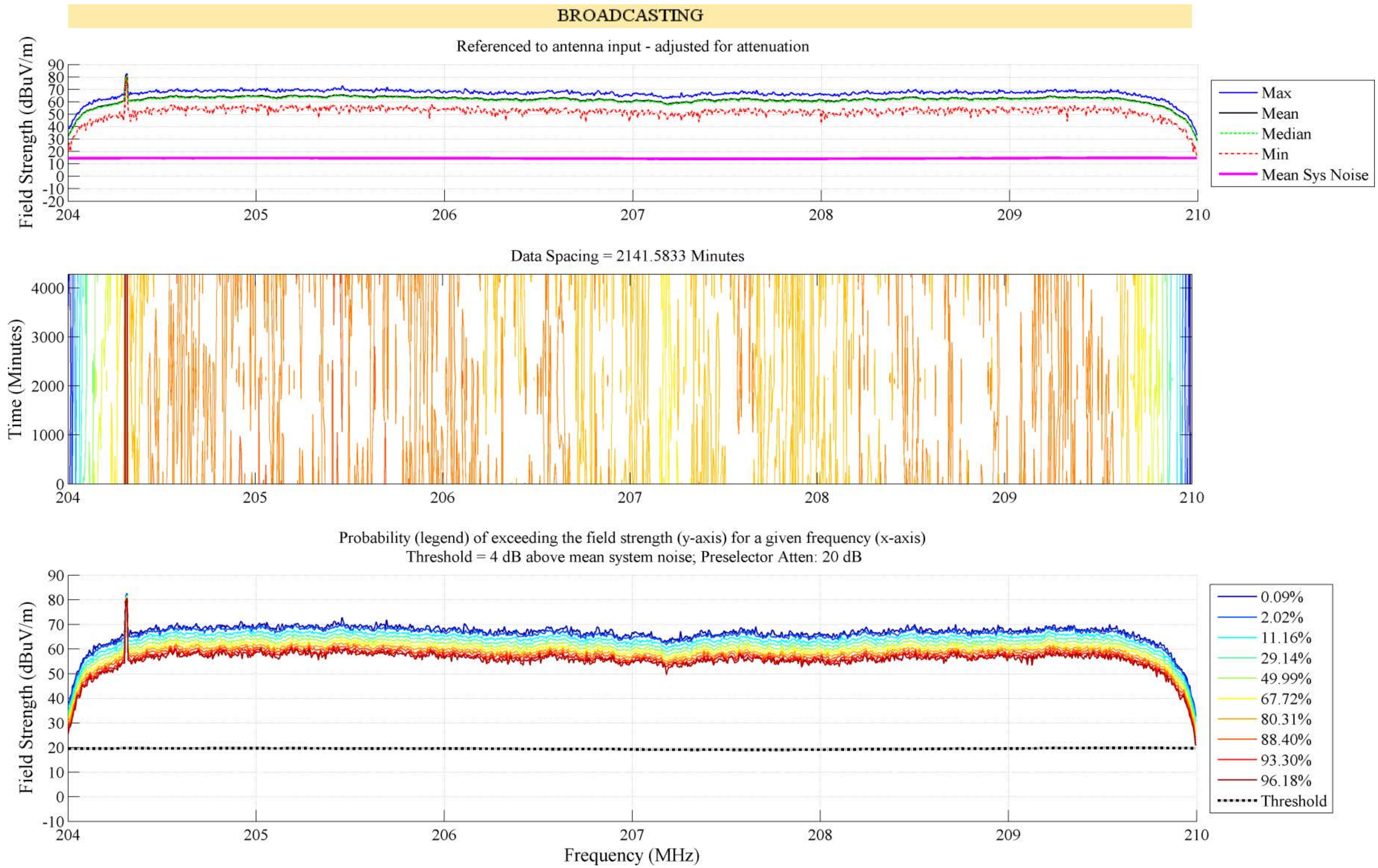

Figure 19. NTIA spectrum survey results from 204 to 210 MHz in Chicago, IL, September 2012.

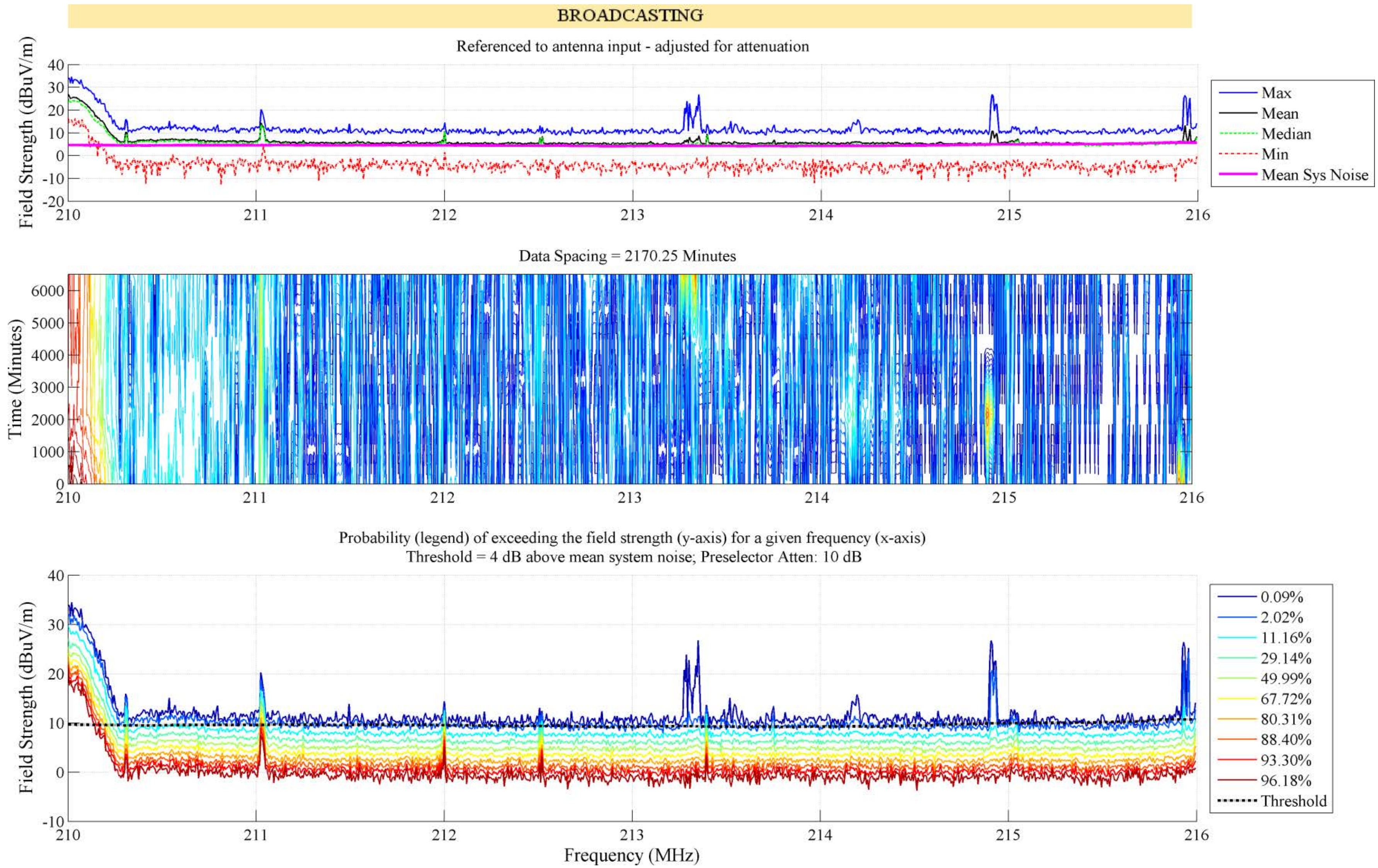

Figure 20. NTIA spectrum survey results from 210 to 216 MHz in Chicago, IL, September 2012.

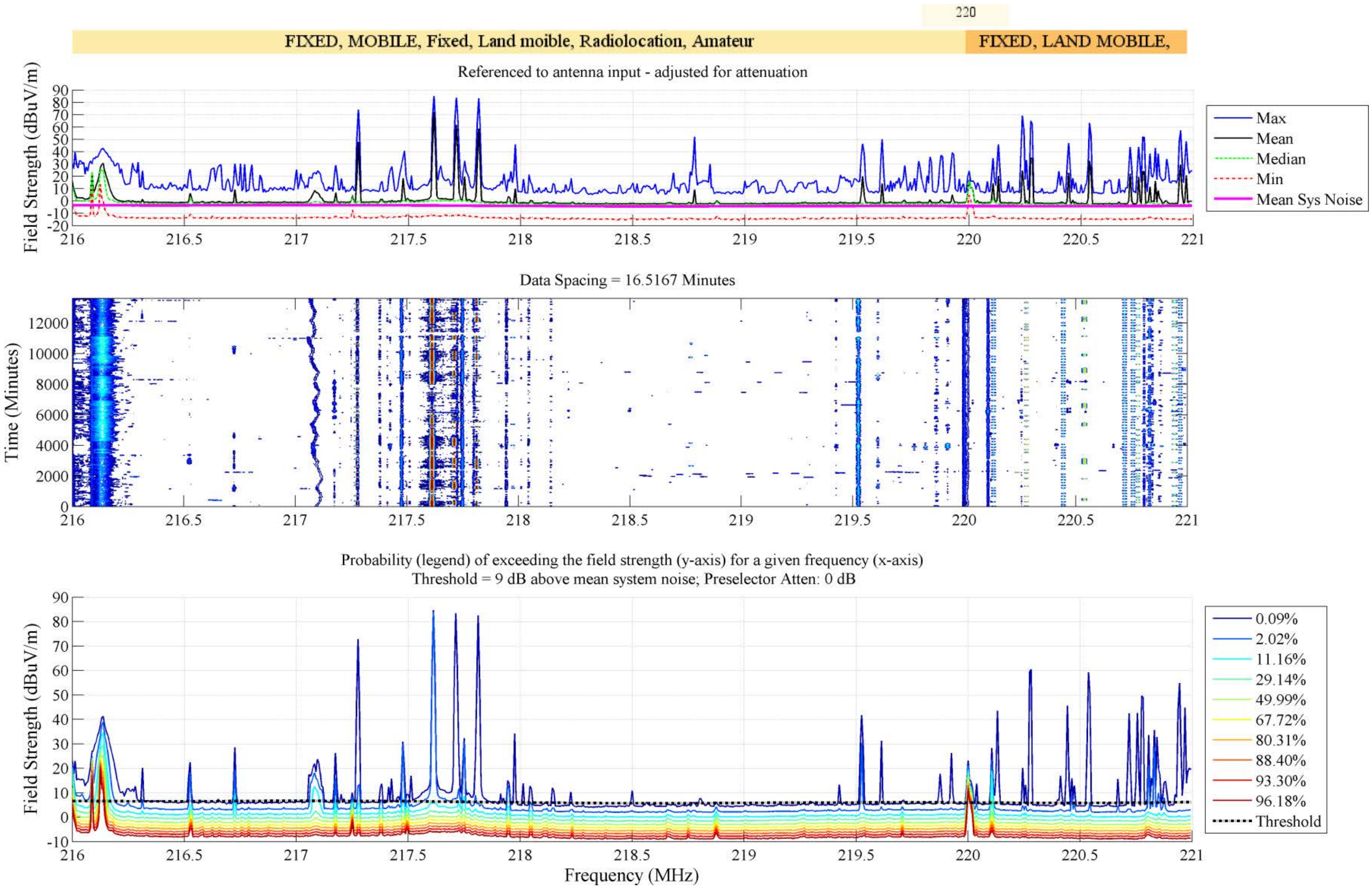

Figure 21. NTIA spectrum survey results from 216 to 221 MHz in Chicago, IL, September 2012.

Figure 22. NTIA spectrum survey results from 221 to 225 MHz in Chicago, IL, September 2012.

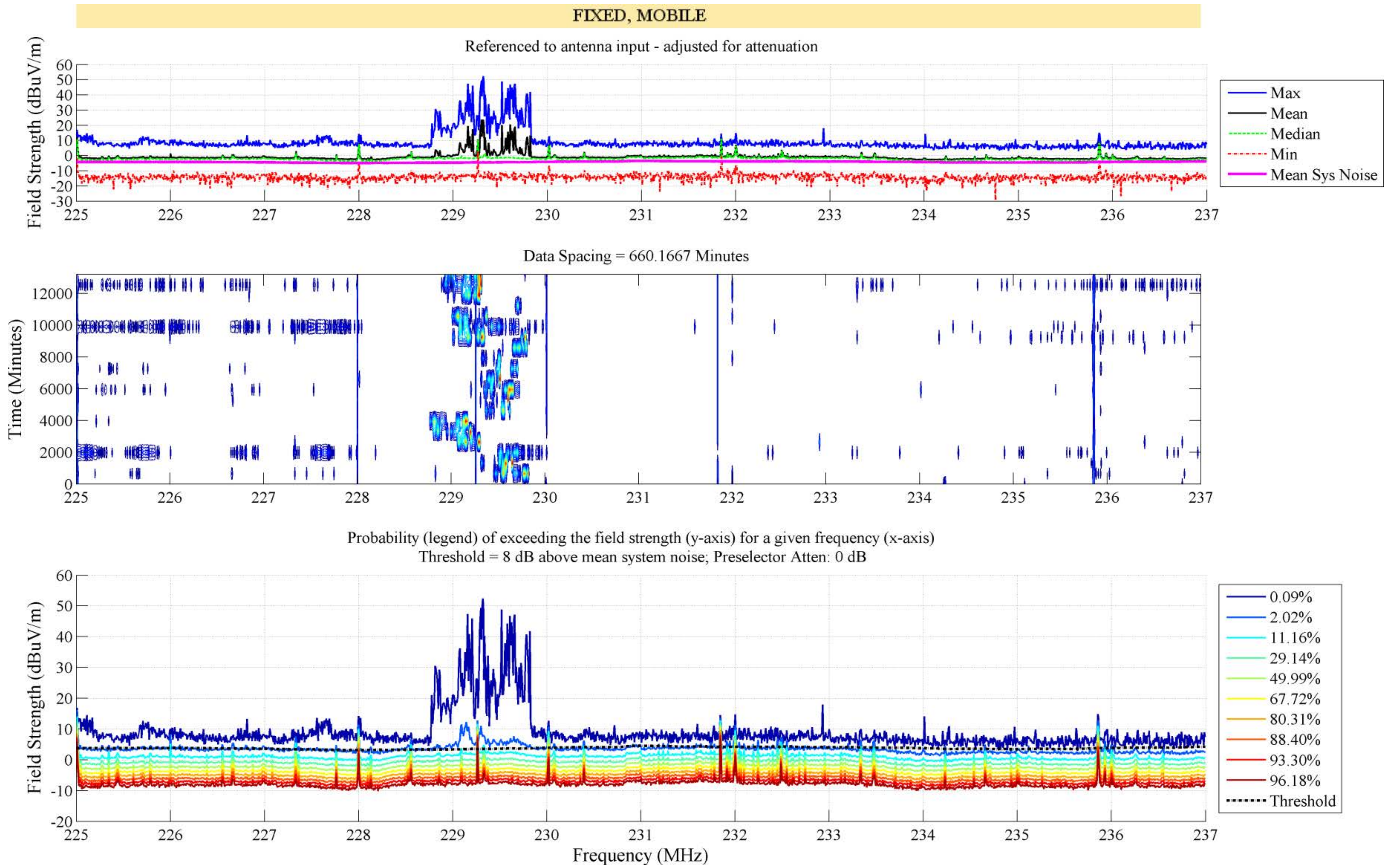

Figure 23. NTIA spectrum survey results from 225 to 237 MHz in Chicago, IL, September 2012.

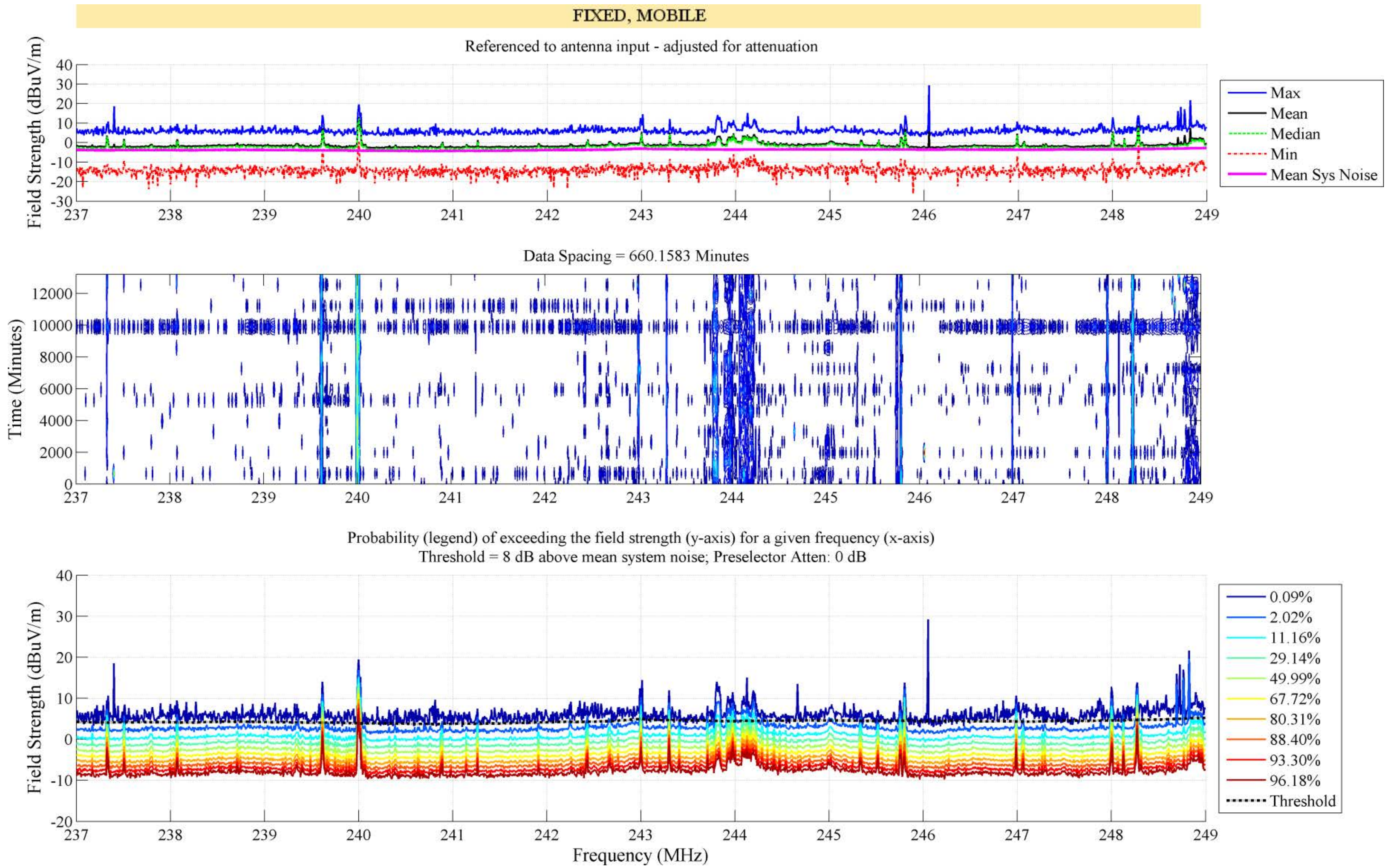

Figure 24. NTIA spectrum survey results from 237 to 249 MHz in Chicago, IL, September 2012.

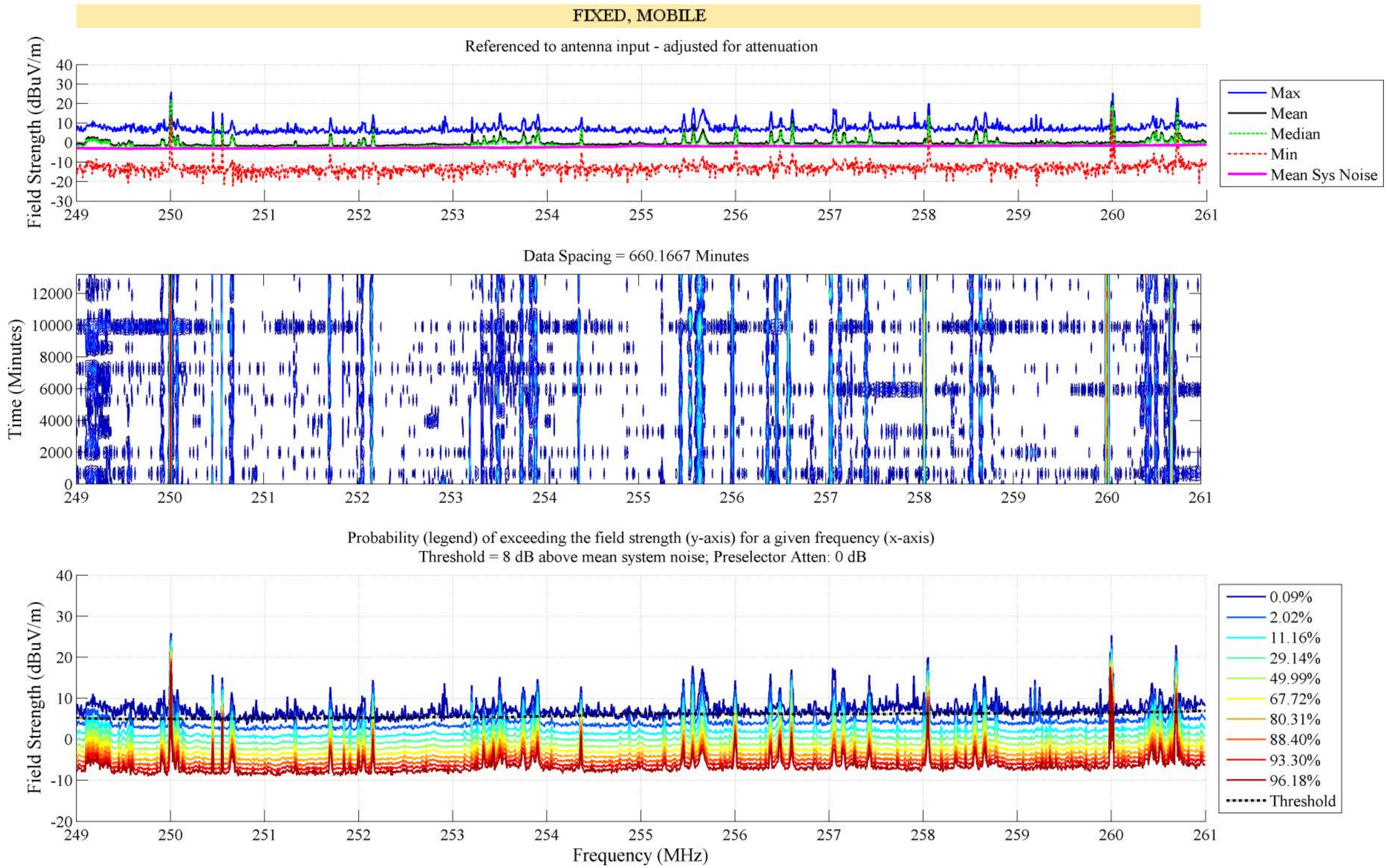

Figure 25. NTIA spectrum survey results from 249 to 261 MHz in Chicago, IL, September 2012.

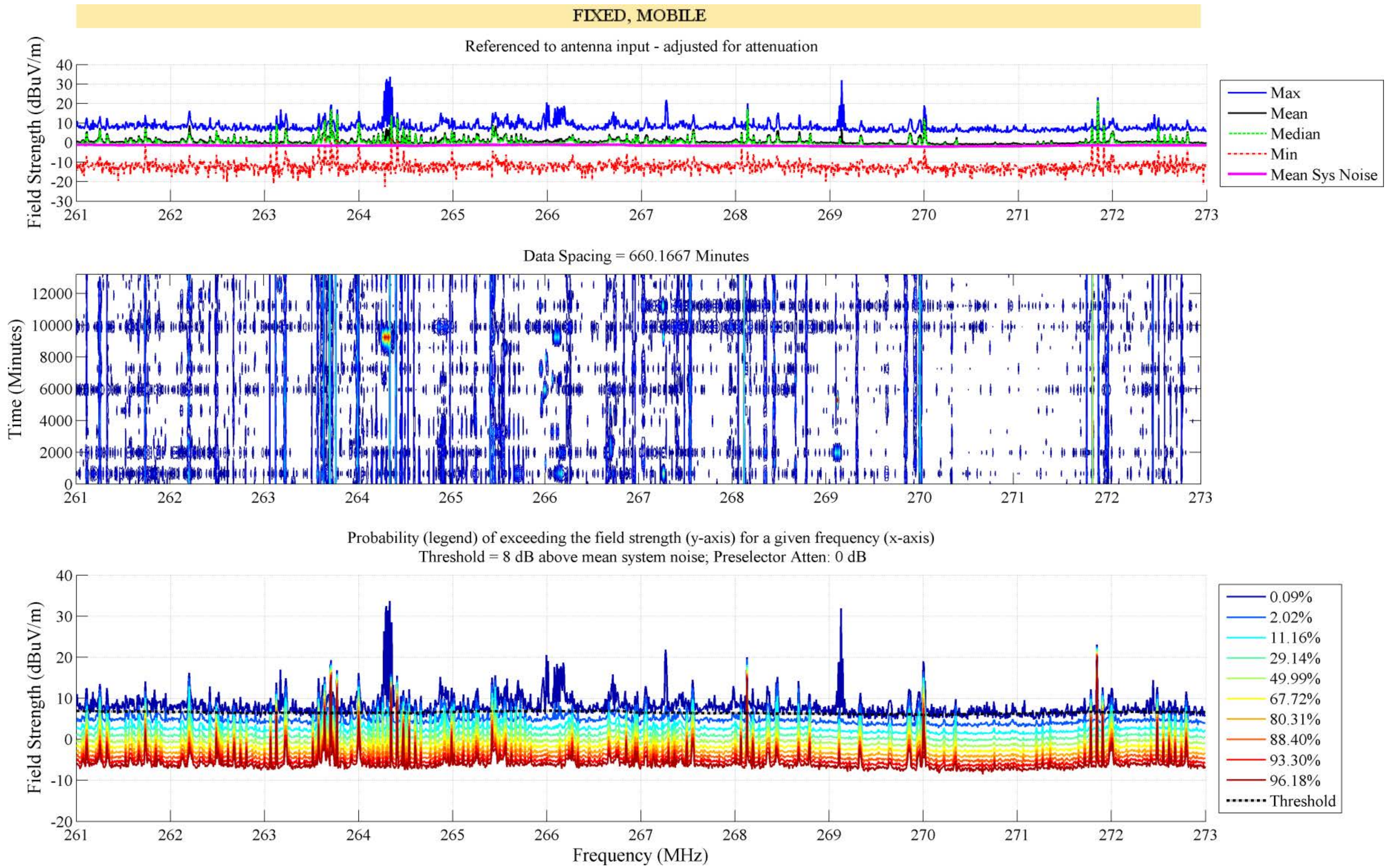

Figure 26. NTIA spectrum survey results from 261 to 273 MHz in Chicago, IL, September 2012.

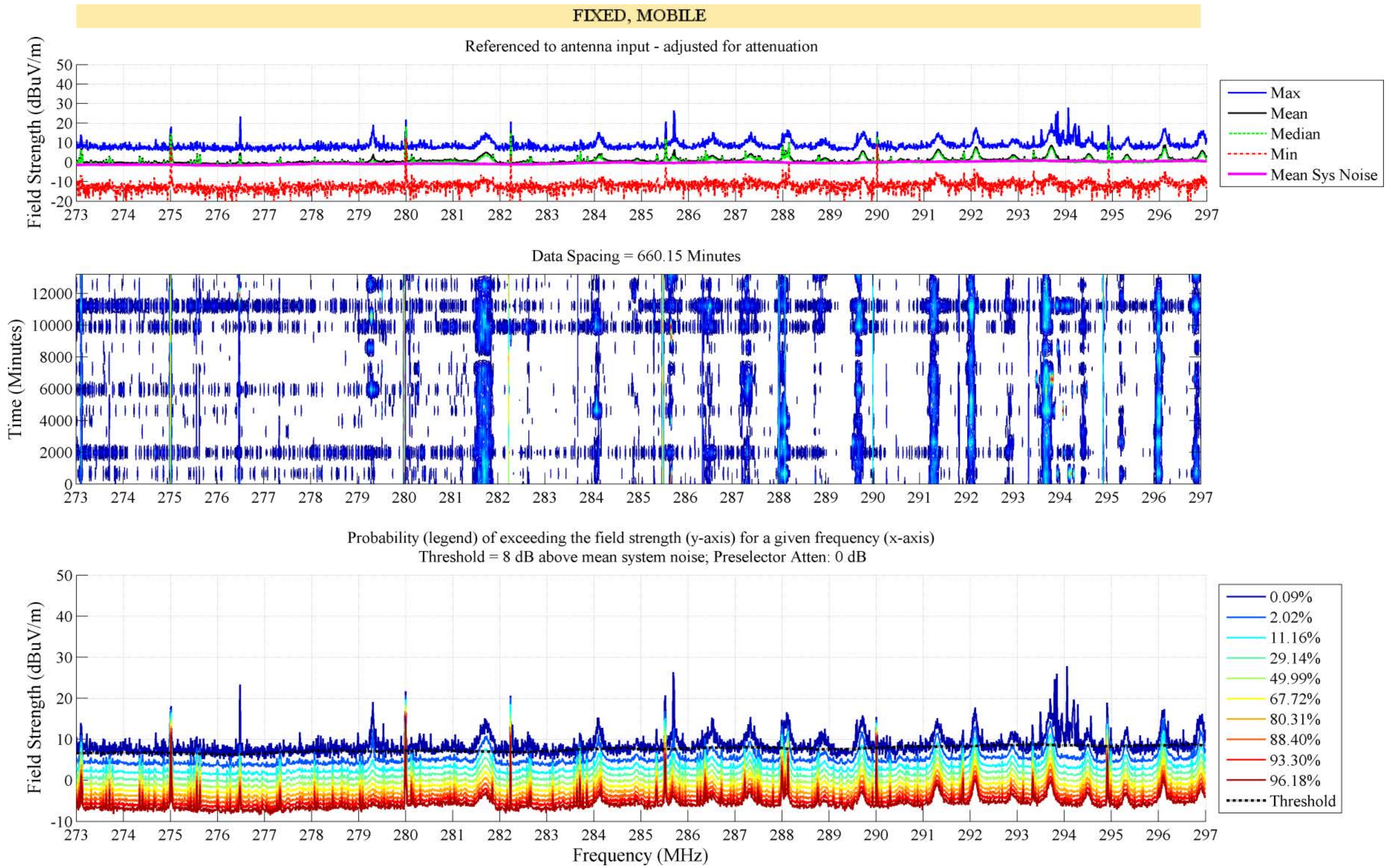

Figure 27. NTIA spectrum survey results from 273 to 297 MHz in Chicago, IL, September 2012.

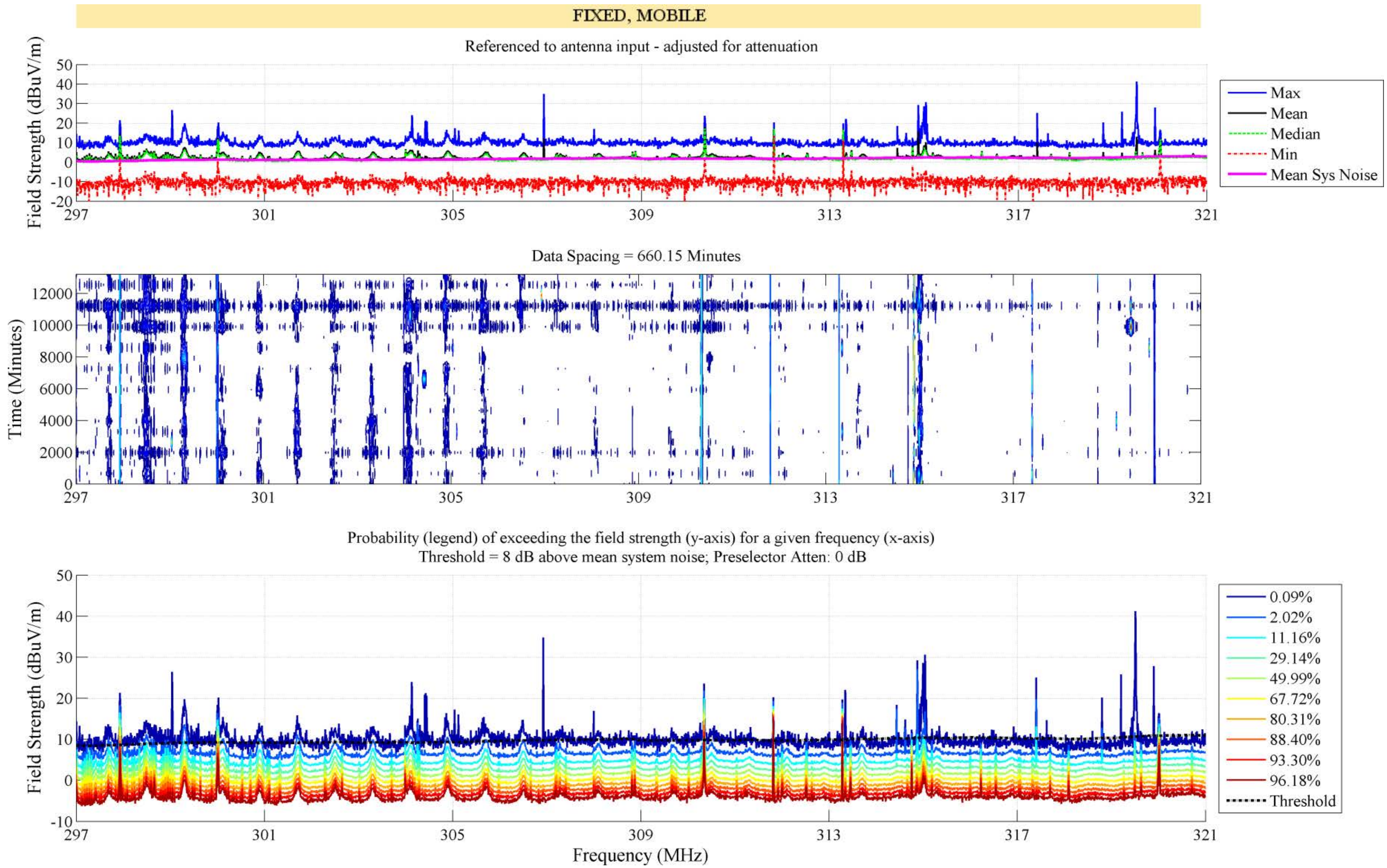

Figure 28. NTIA spectrum survey results from 297 to 321 MHz in Chicago, IL, September 2012.

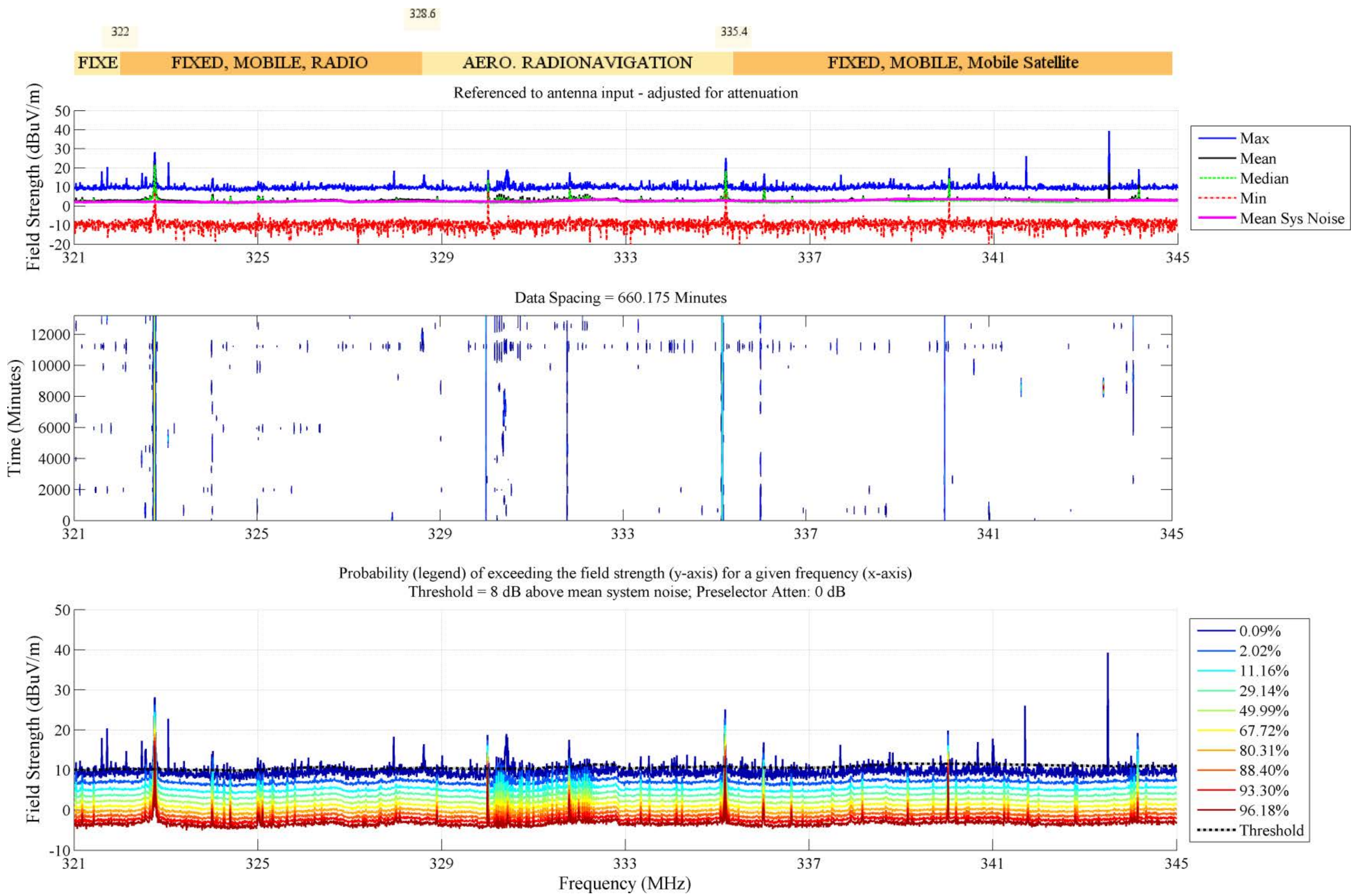

Figure 29. NTIA spectrum survey results from 321 to 345 MHz in Chicago, IL, September 2012.

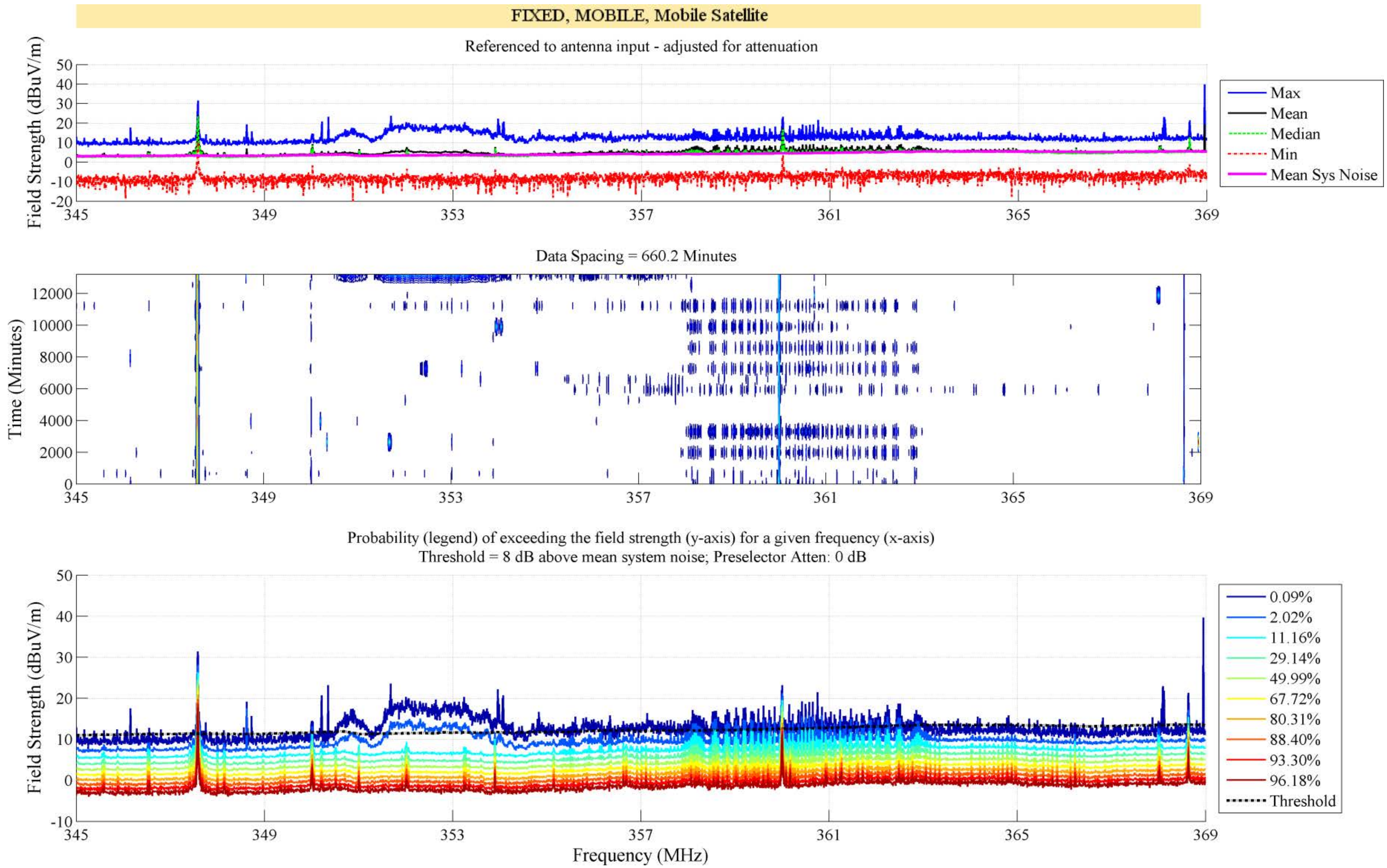

Figure 30. NTIA spectrum survey results from 345 to 369 MHz in Chicago, IL, September 2012.

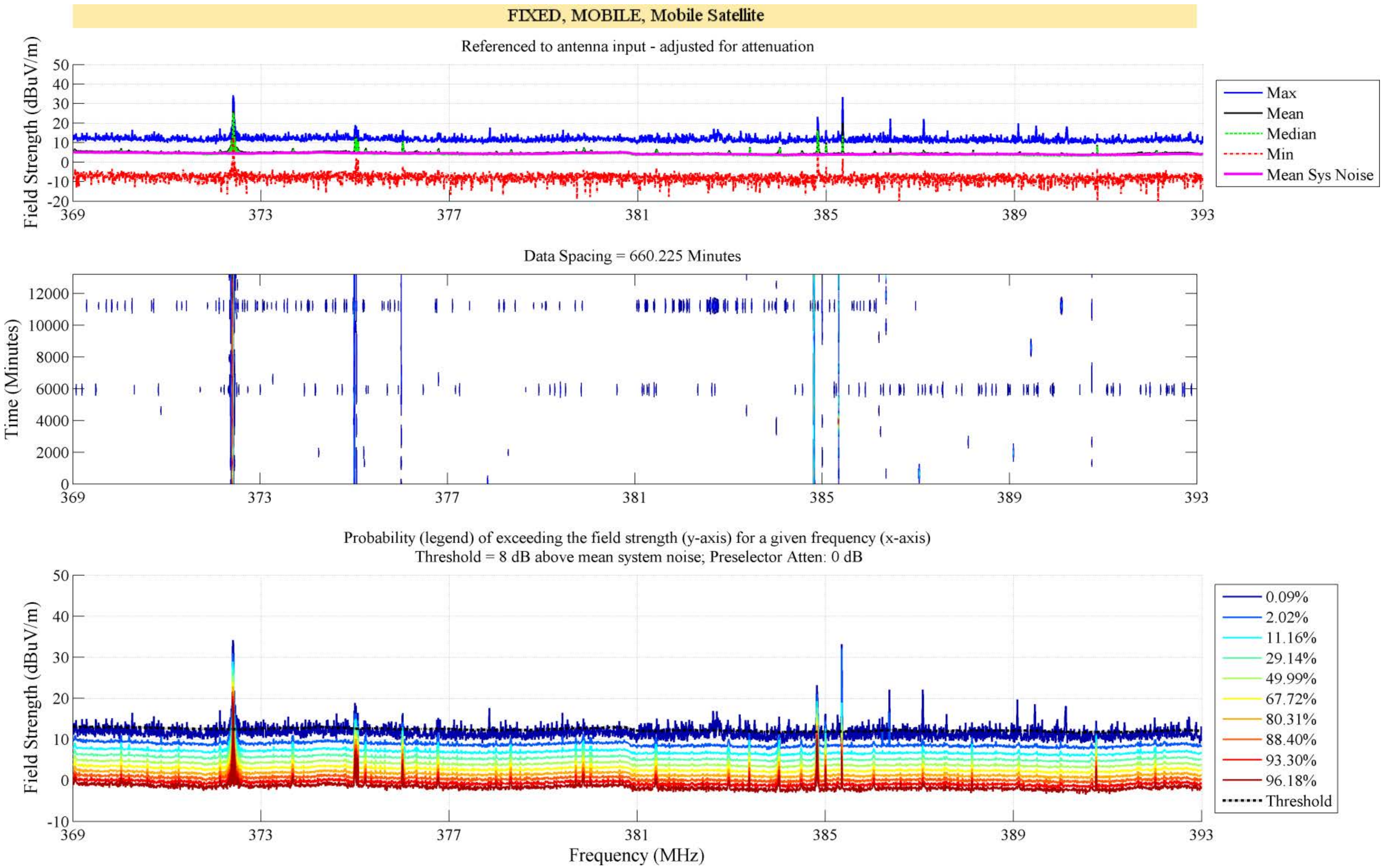

Figure 31. NTIA spectrum survey results from 369 to 393 MHz in Chicago, IL, September 2012.

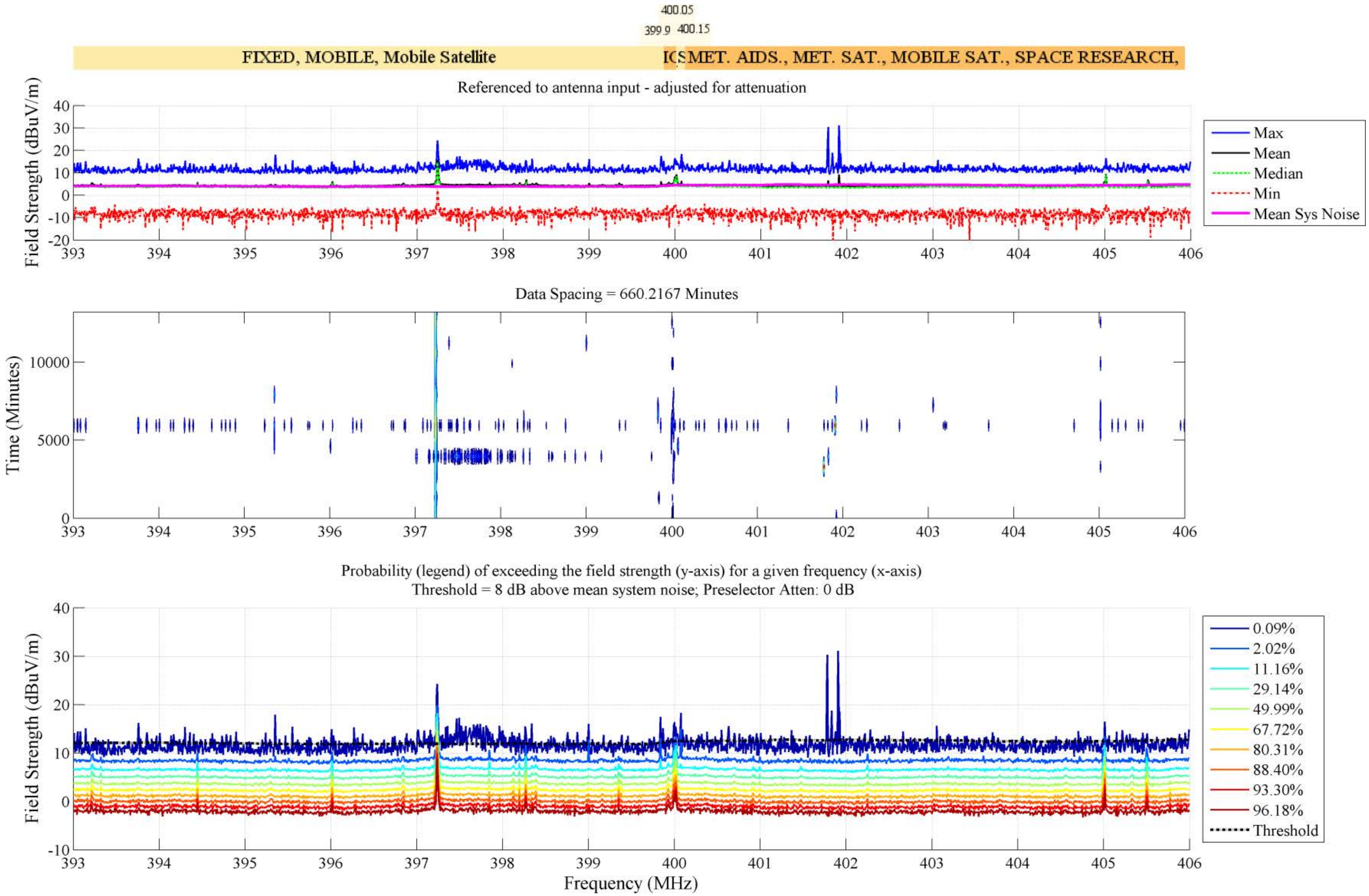

Figure 32. NTIA spectrum survey results from 393 to 406 MHz in Chicago, IL, September 2012.

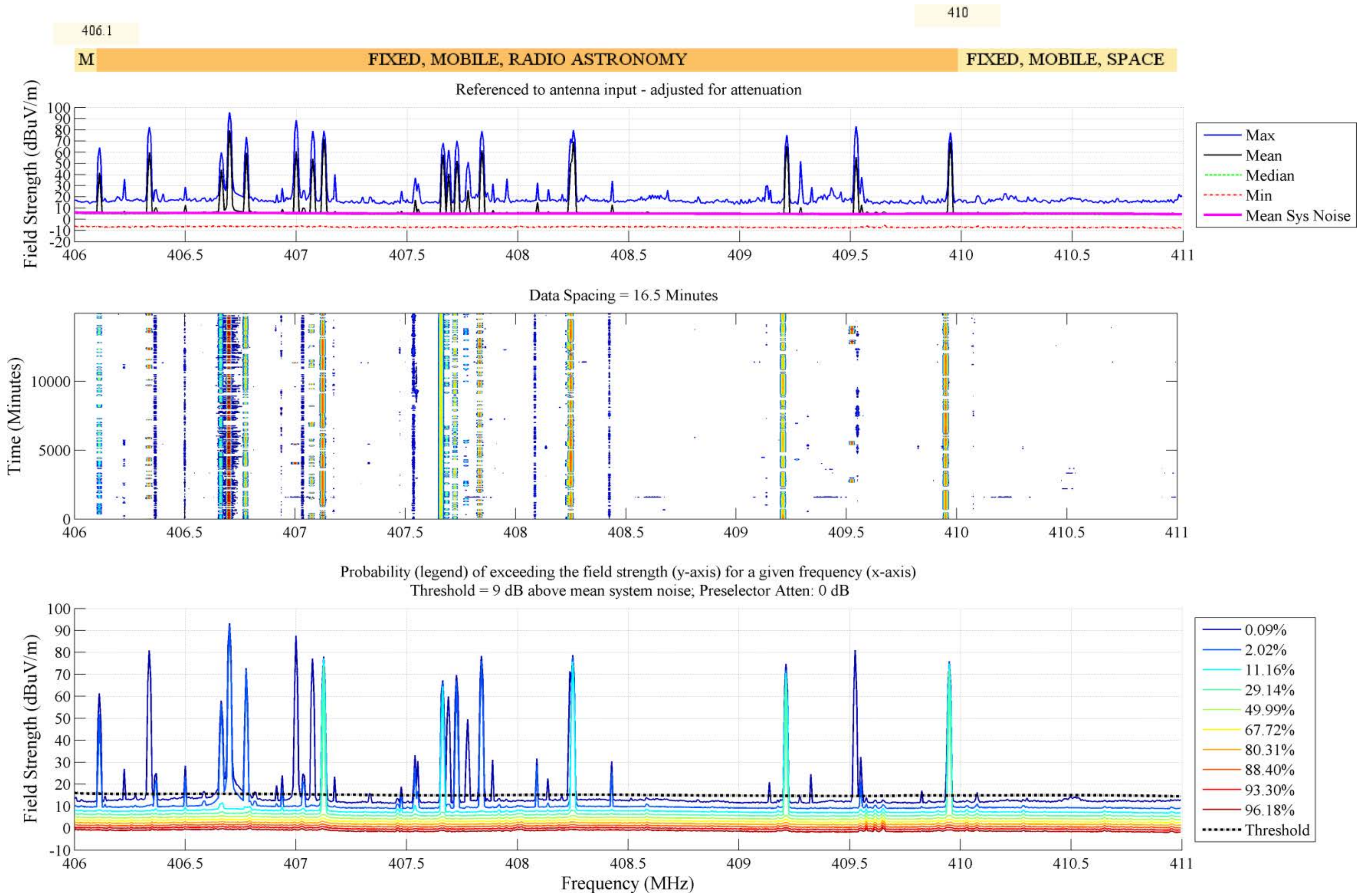

Figure 33. NTIA spectrum survey results from 406 to 411 MHz in Chicago, IL, September 2012.

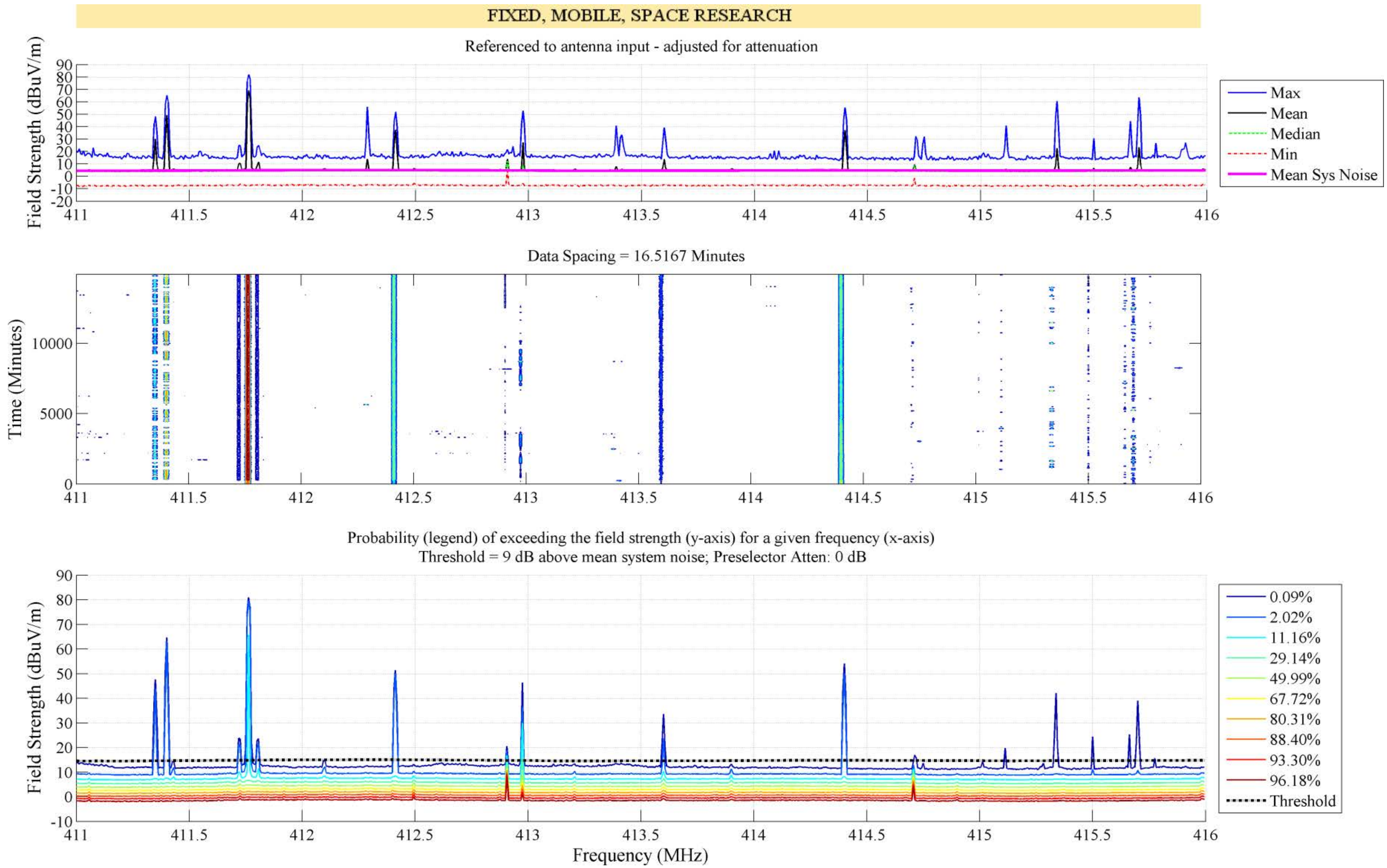

Figure 34. NTIA spectrum survey results from 411 to 416 MHz in Chicago, IL, September 2012.

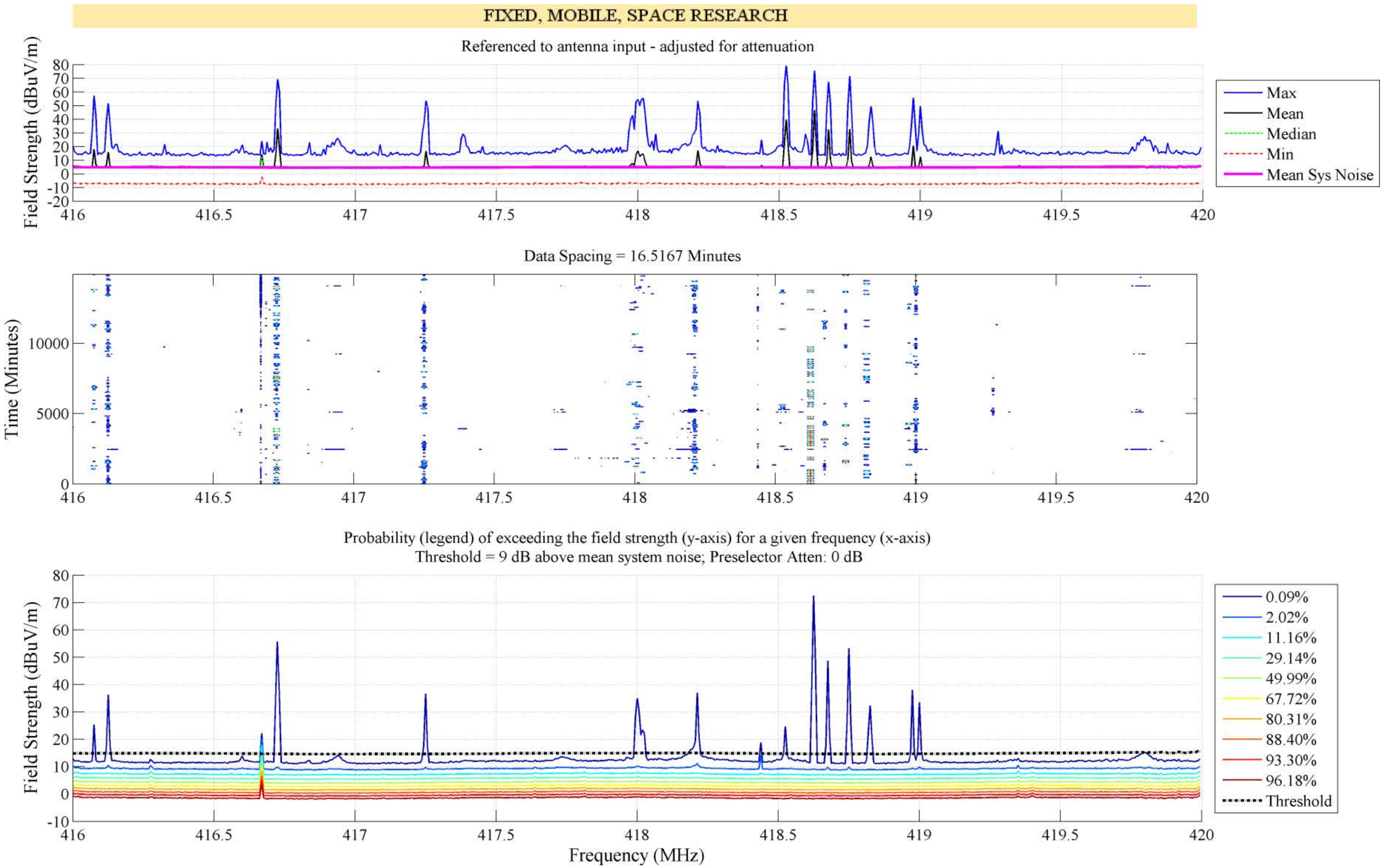

Figure 35. NTIA spectrum survey results from 416 to 420 MHz in Chicago, IL, September 2012.

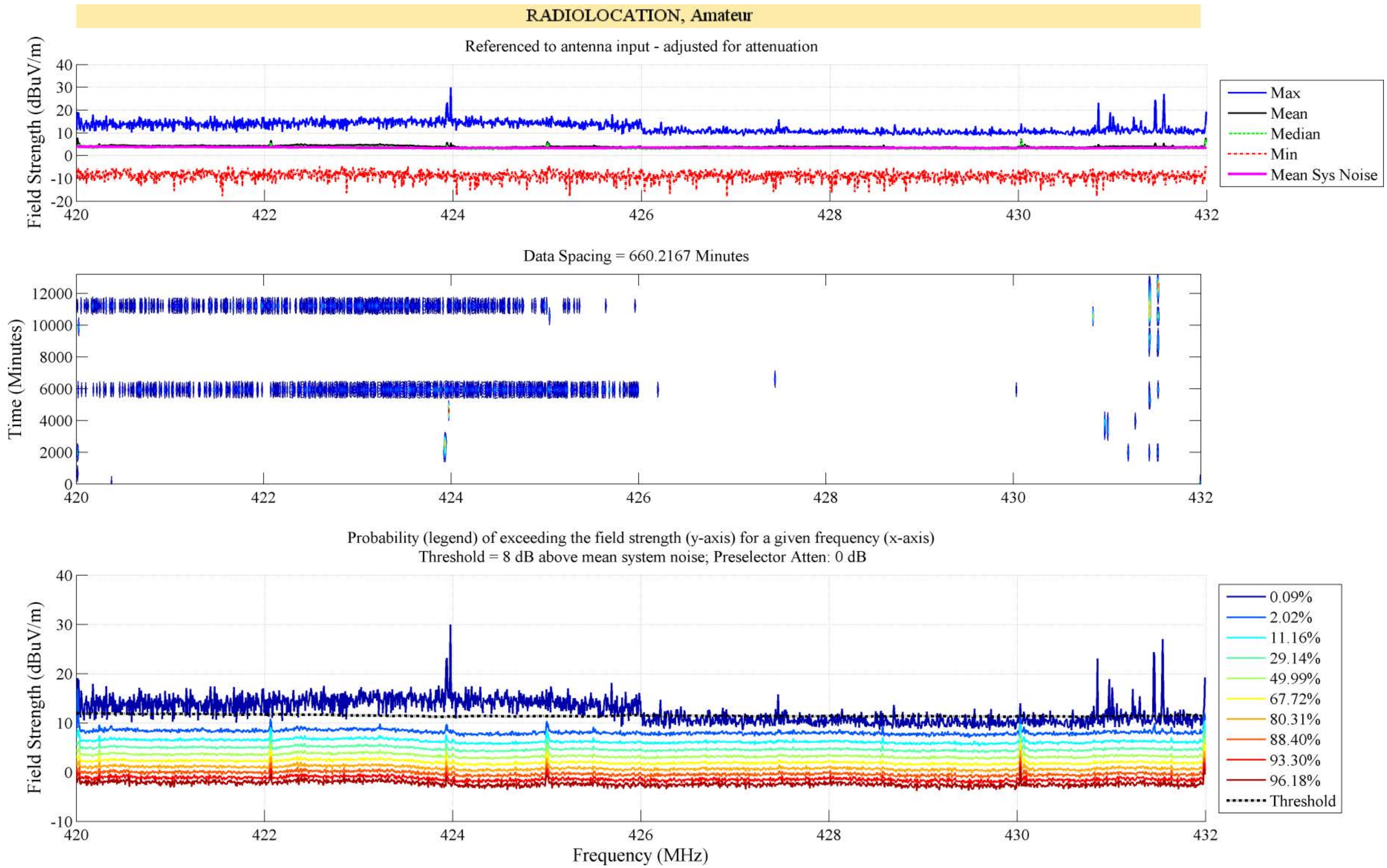

Figure 36. NTIA spectrum survey results from 420 to 432 MHz in Chicago, IL, September 2012.

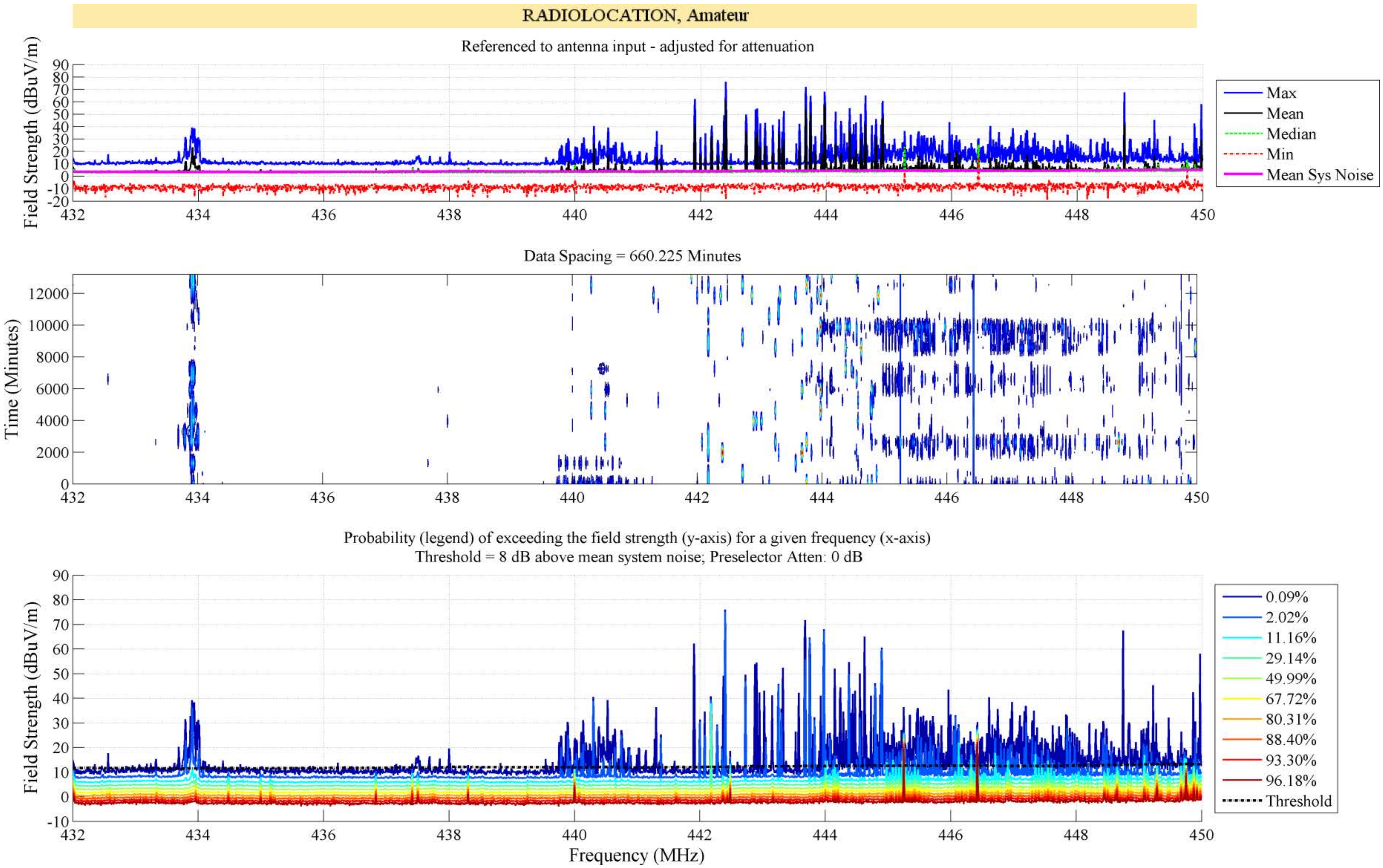

Figure 37. NTIA spectrum survey results from 432 to 450 MHz in Chicago, IL, September 2012.

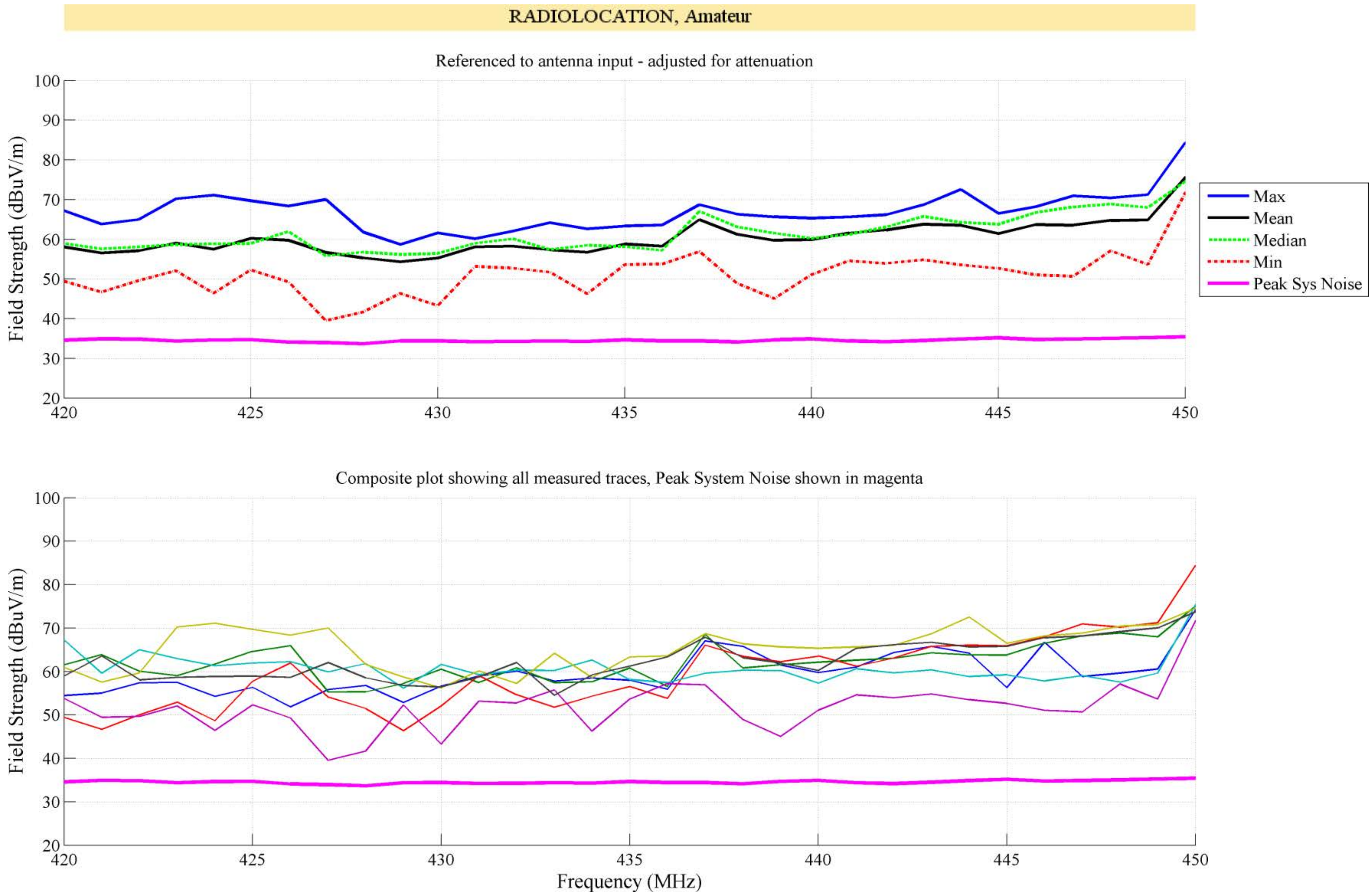

Figure 38. NTIA spectrum survey results from 420 to 450 MHz in Chicago, IL, September 2012. This measurement was taken using the stepped-spectrum measurement algorithm.

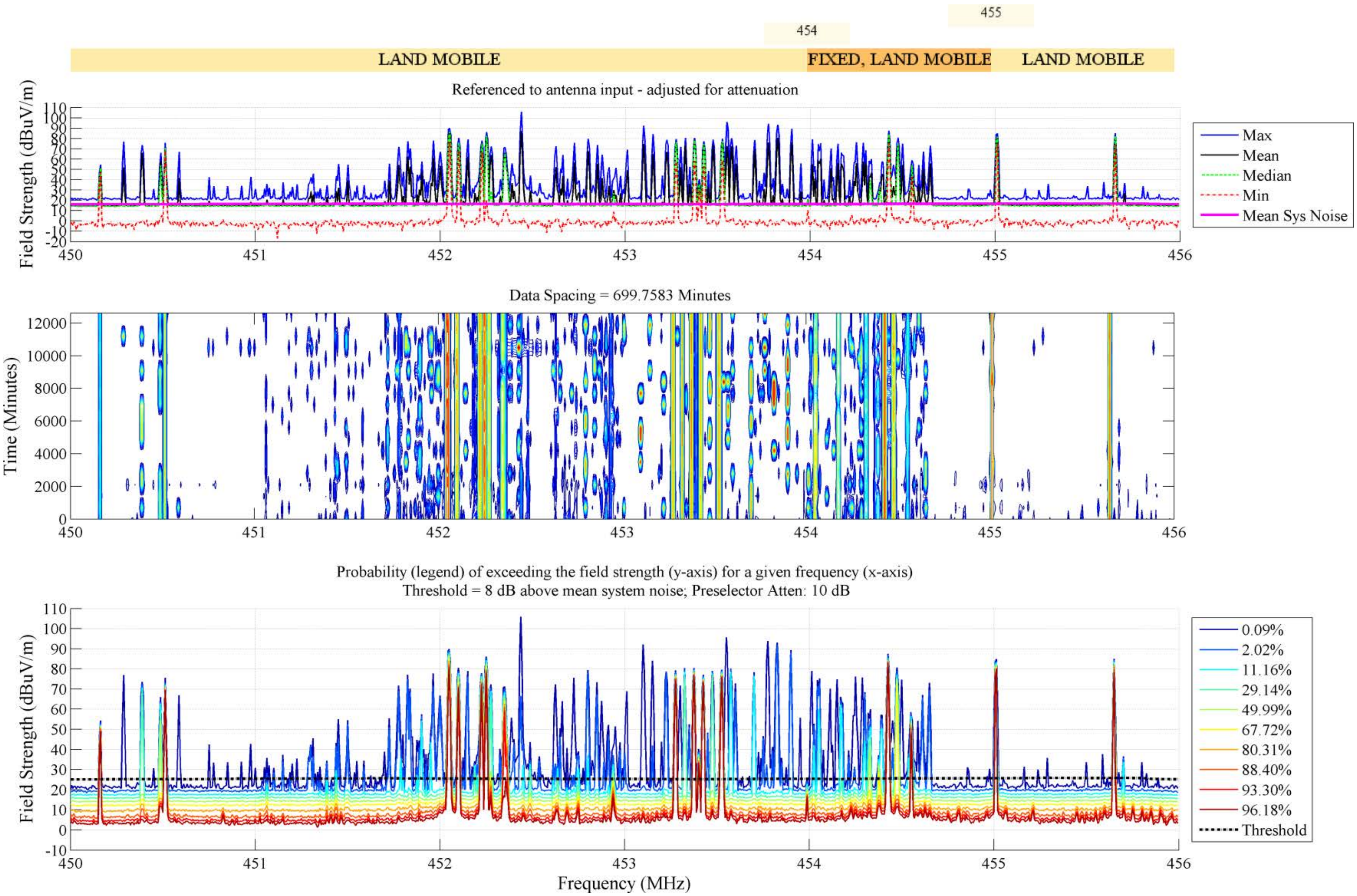

Figure 39. NTIA spectrum survey results from 450 to 456 MHz in Chicago, IL, September 2012.

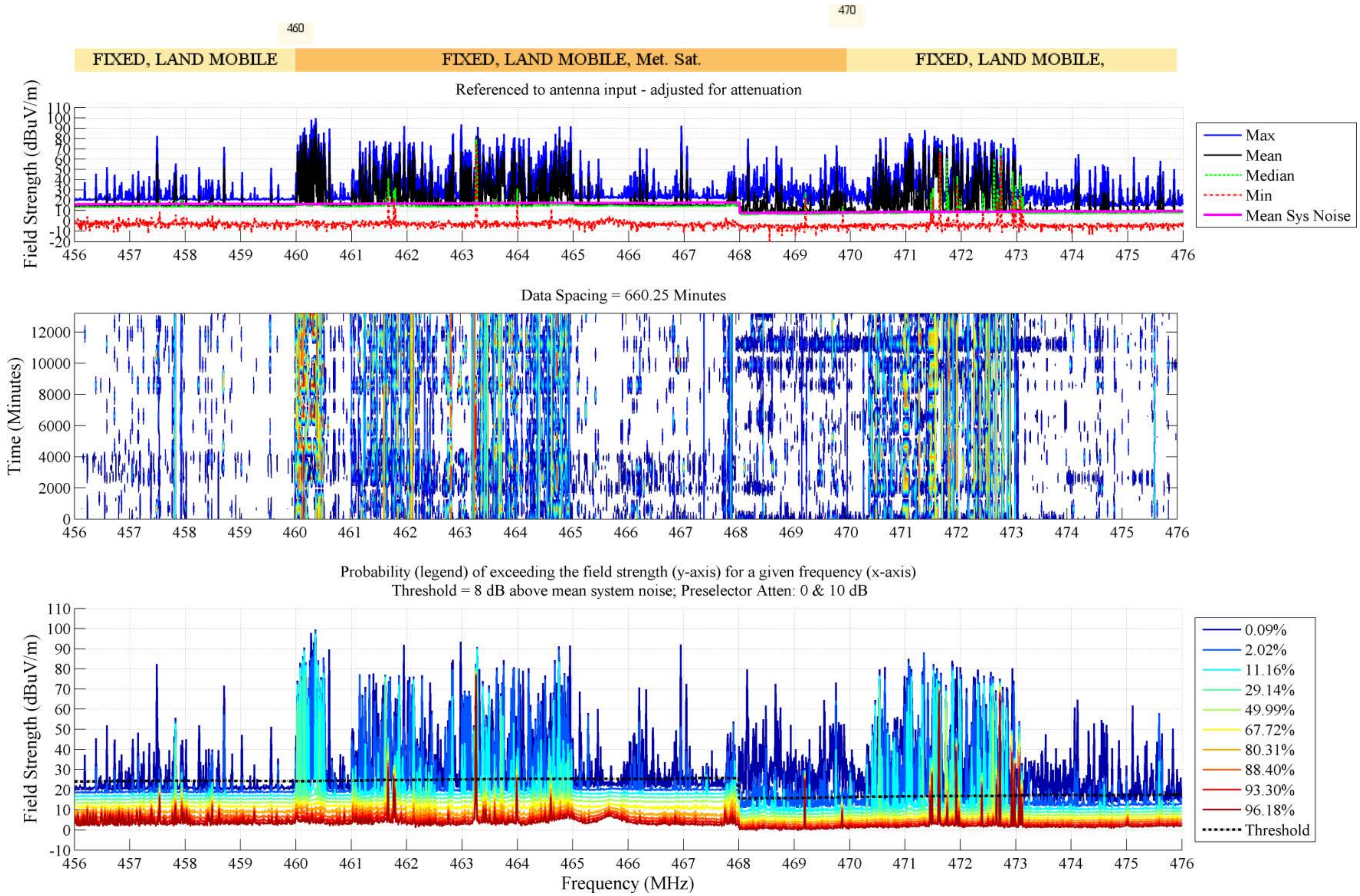

Figure 40. NTIA spectrum survey results from 456 to 476 MHz in Chicago, IL, September 2012.

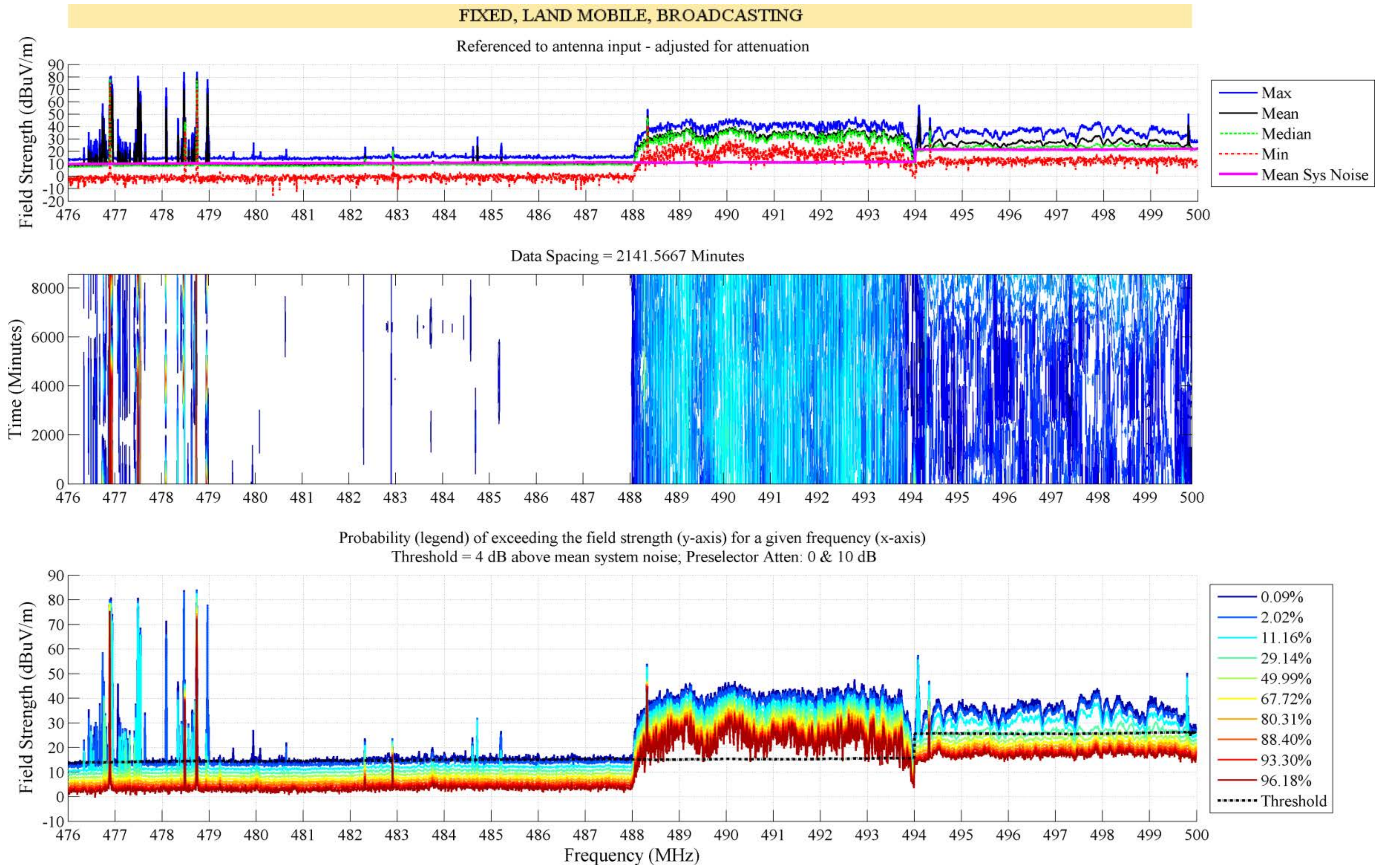

Figure 41. NTIA spectrum survey results from 476 to 500 MHz in Chicago, IL, September 2012.

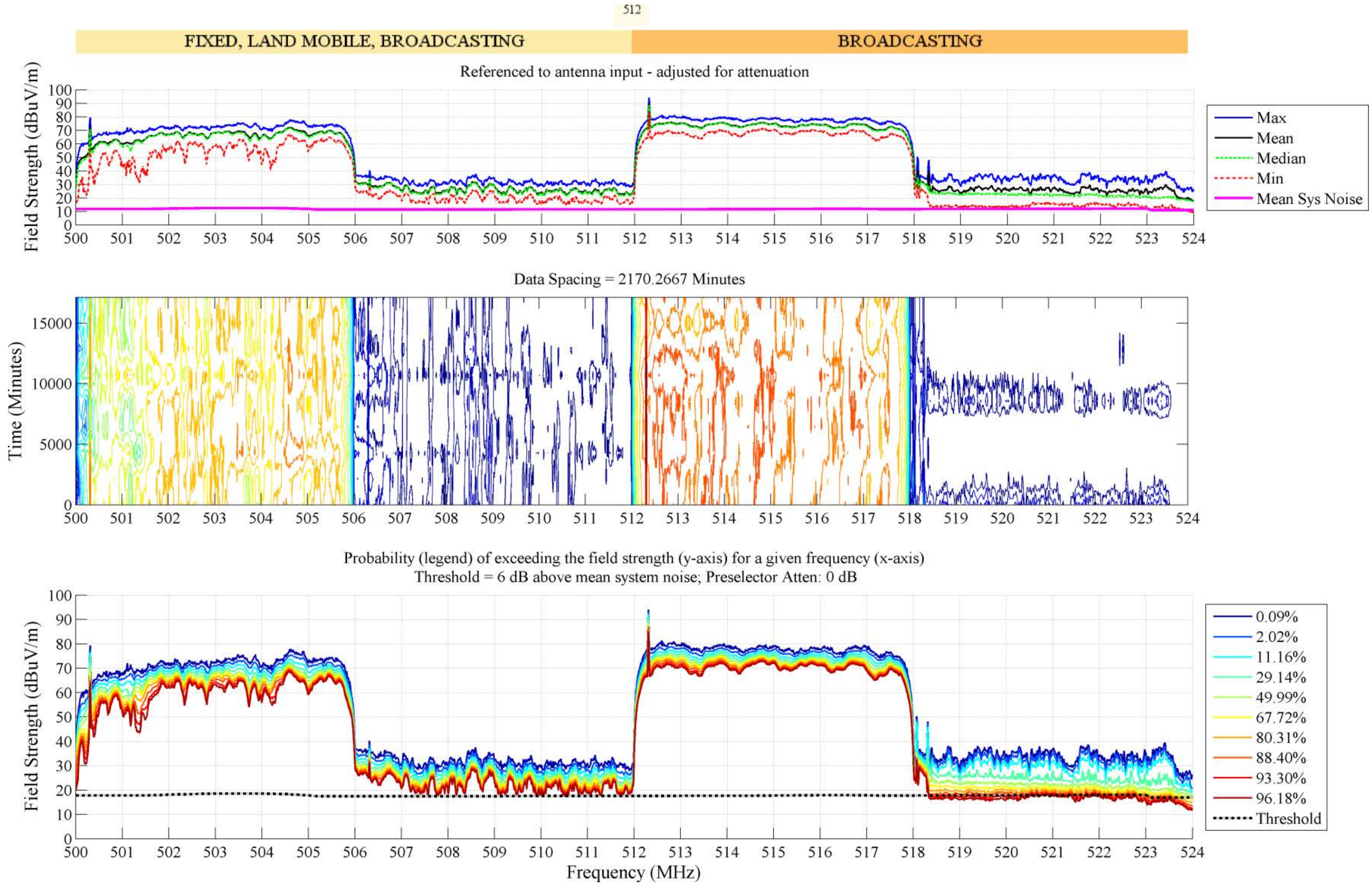

Figure 42. NTIA spectrum survey results from 500 to 524 MHz in Chicago, IL, September 2012.

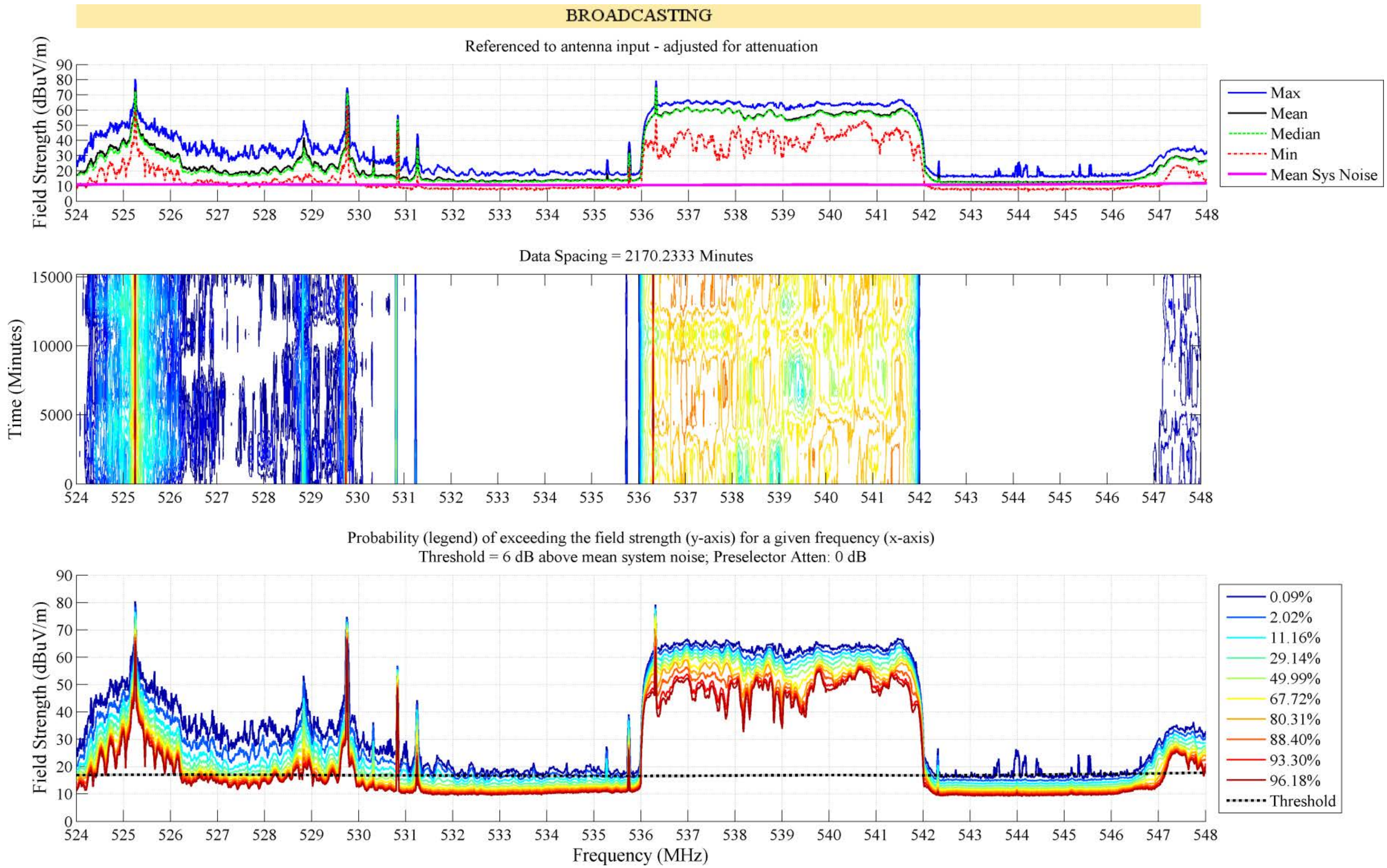

Figure 43. NTIA spectrum survey results from 524 to 548 MHz in Chicago, IL, September 2012.

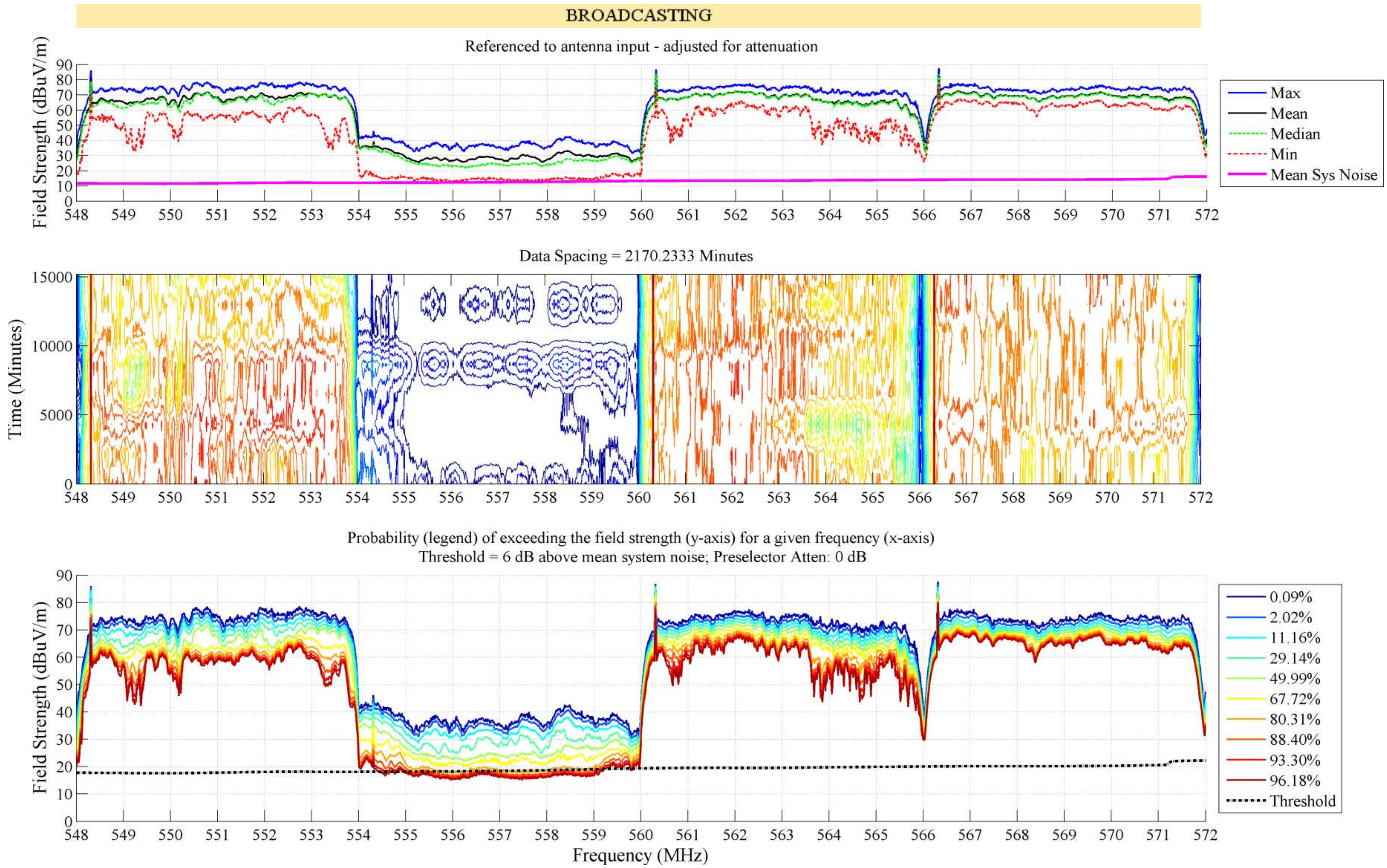

Figure 44. NTIA spectrum survey results from 548 to 572 MHz in Chicago, IL, September 2012.

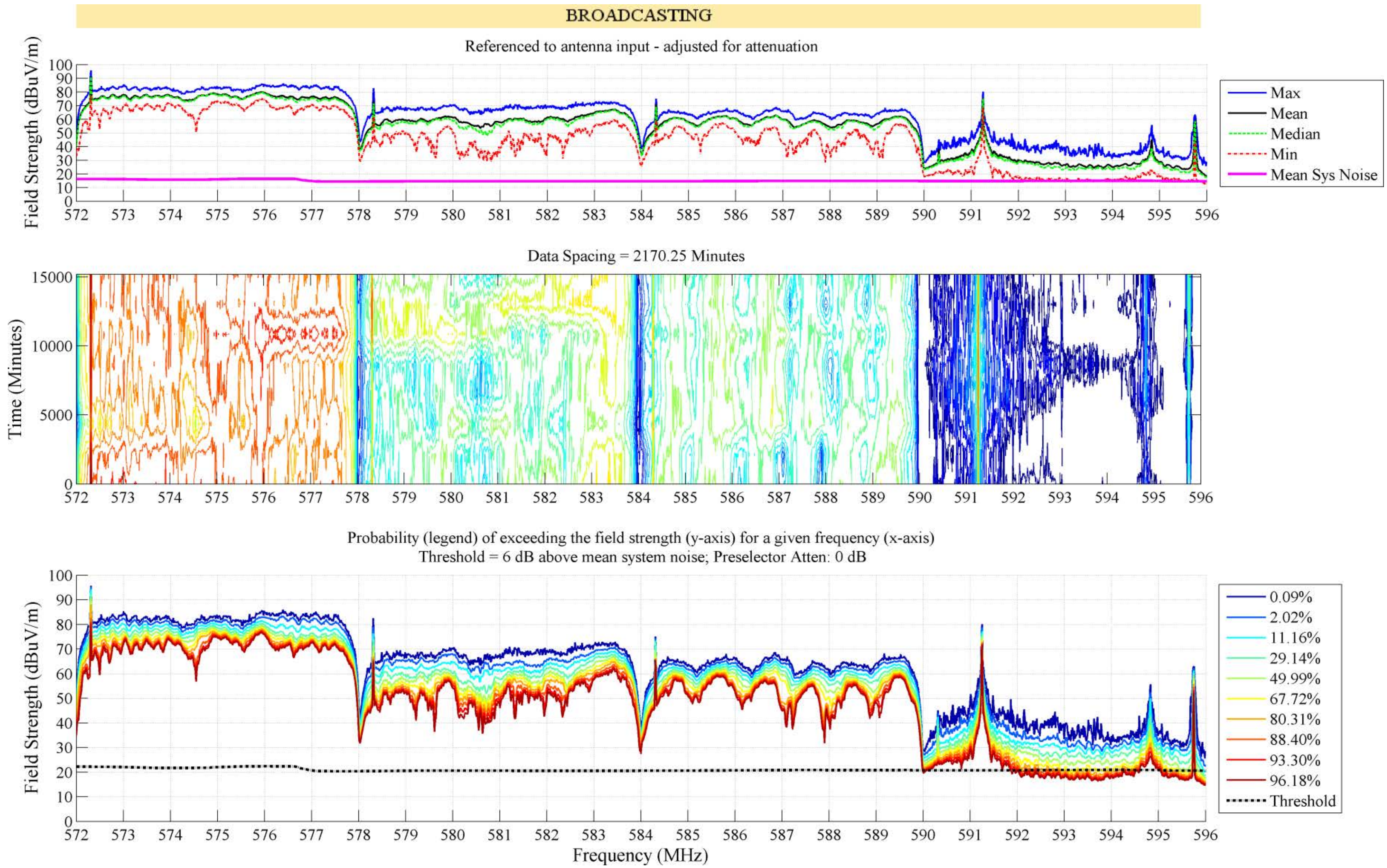

Figure 45. NTIA spectrum survey results from 572 to 596 MHz in Chicago, IL, September 2012.

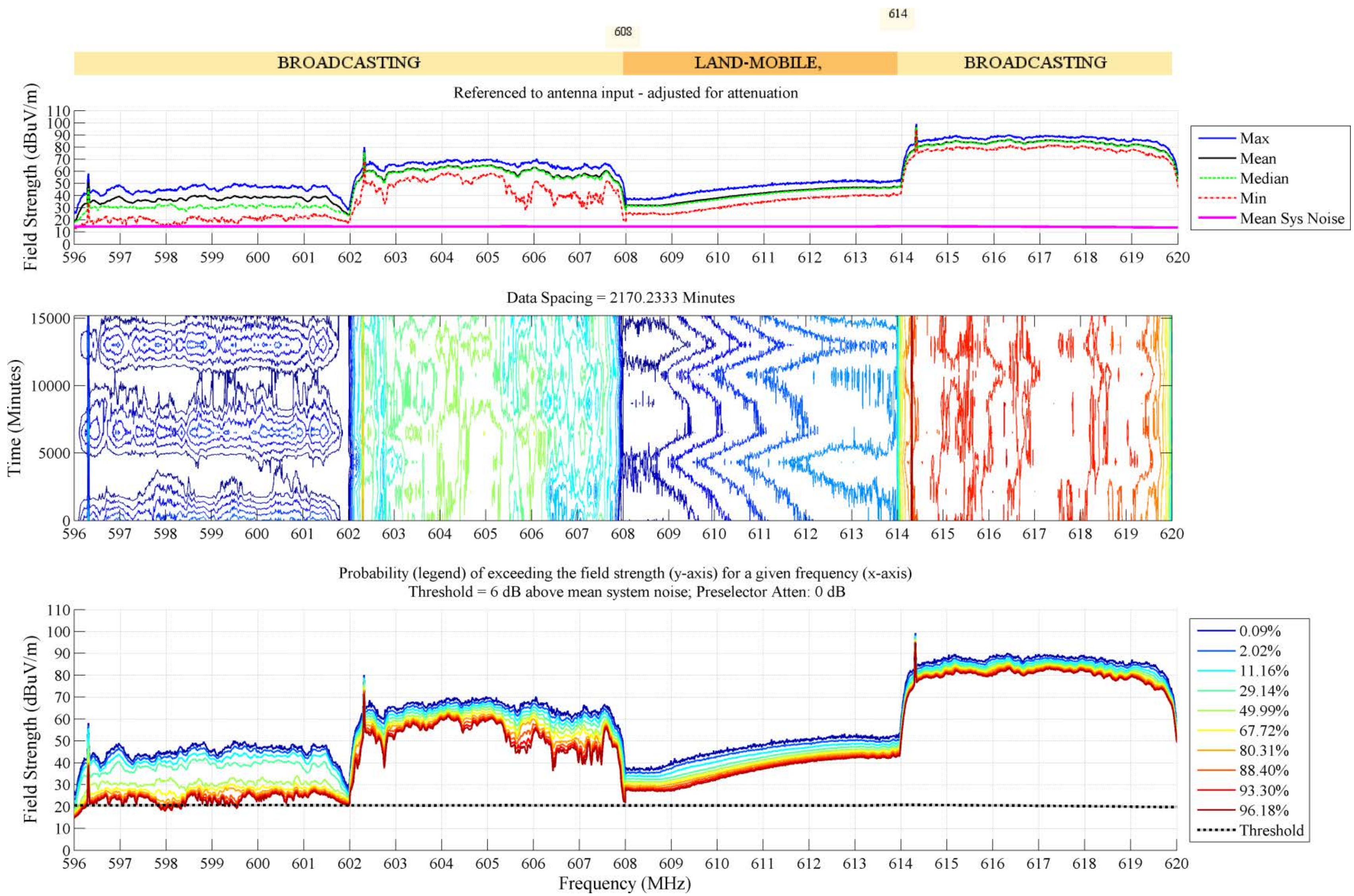

Figure 46. NTIA spectrum survey results from 596 to 620 MHz in Chicago, IL, September 2012.

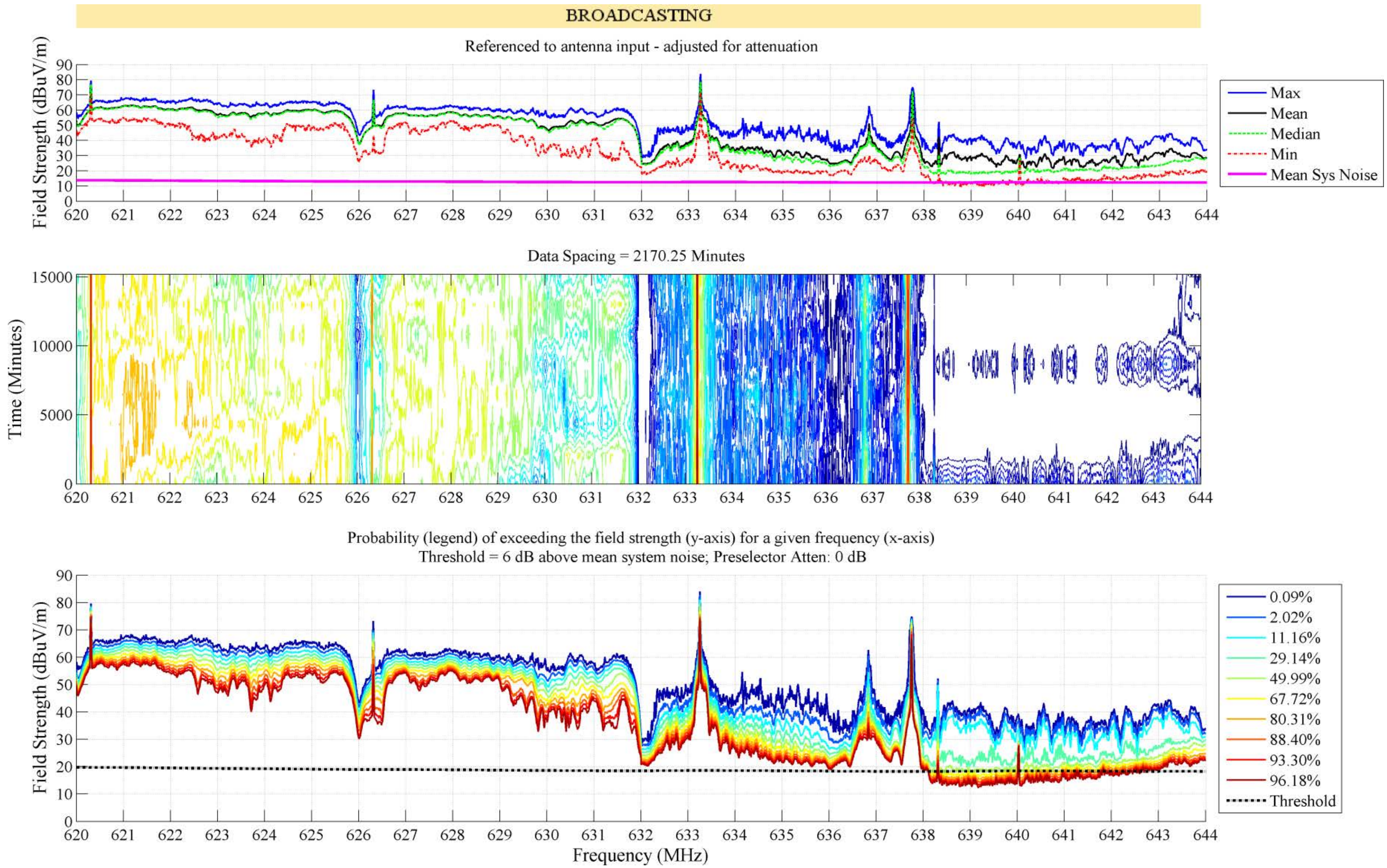

Figure 47. NTIA spectrum survey results from 620 to 644 MHz in Chicago, IL, September 2012.

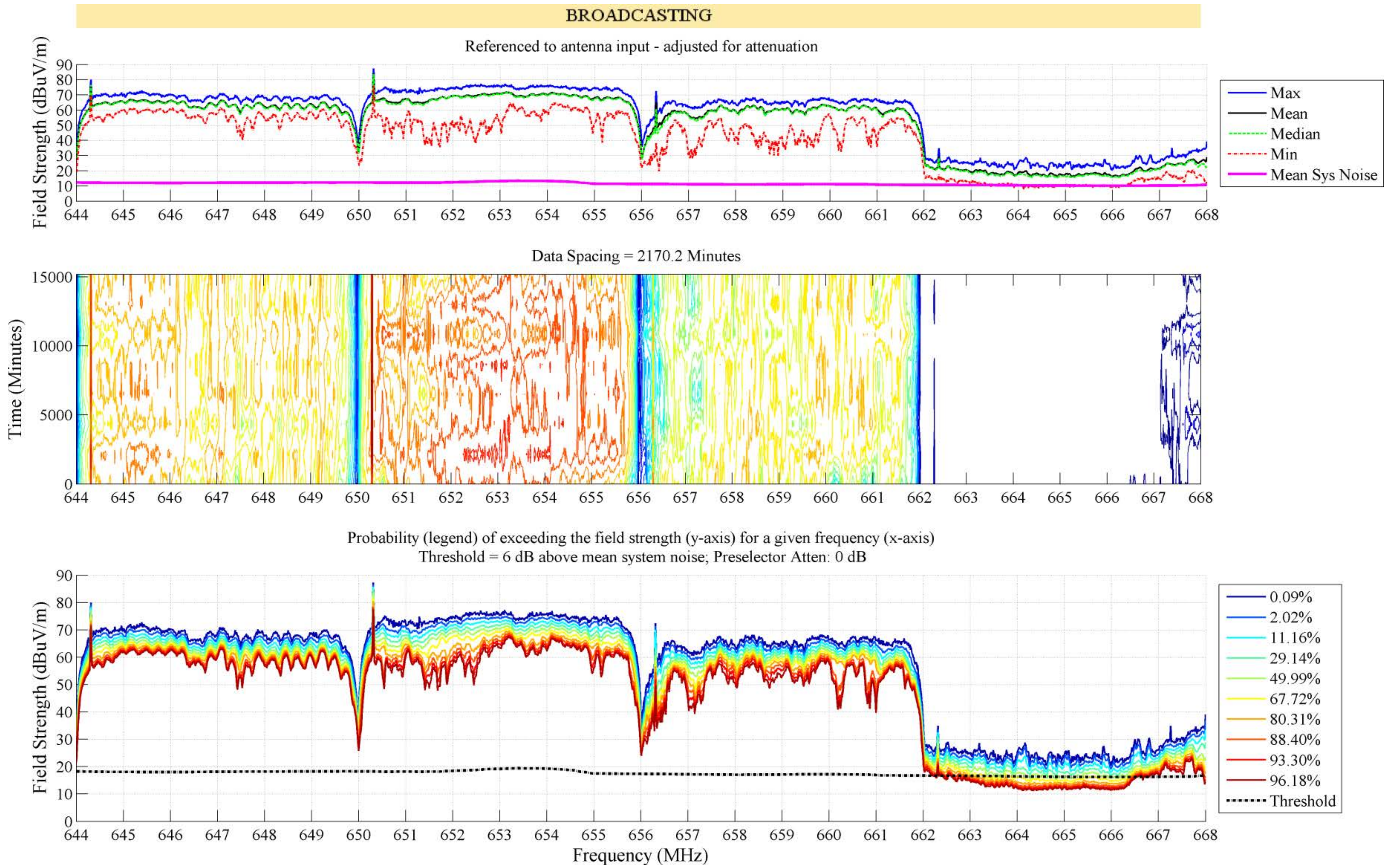

Figure 48. NTIA spectrum survey results from 644 to 668 MHz in Chicago, IL, September 2012.

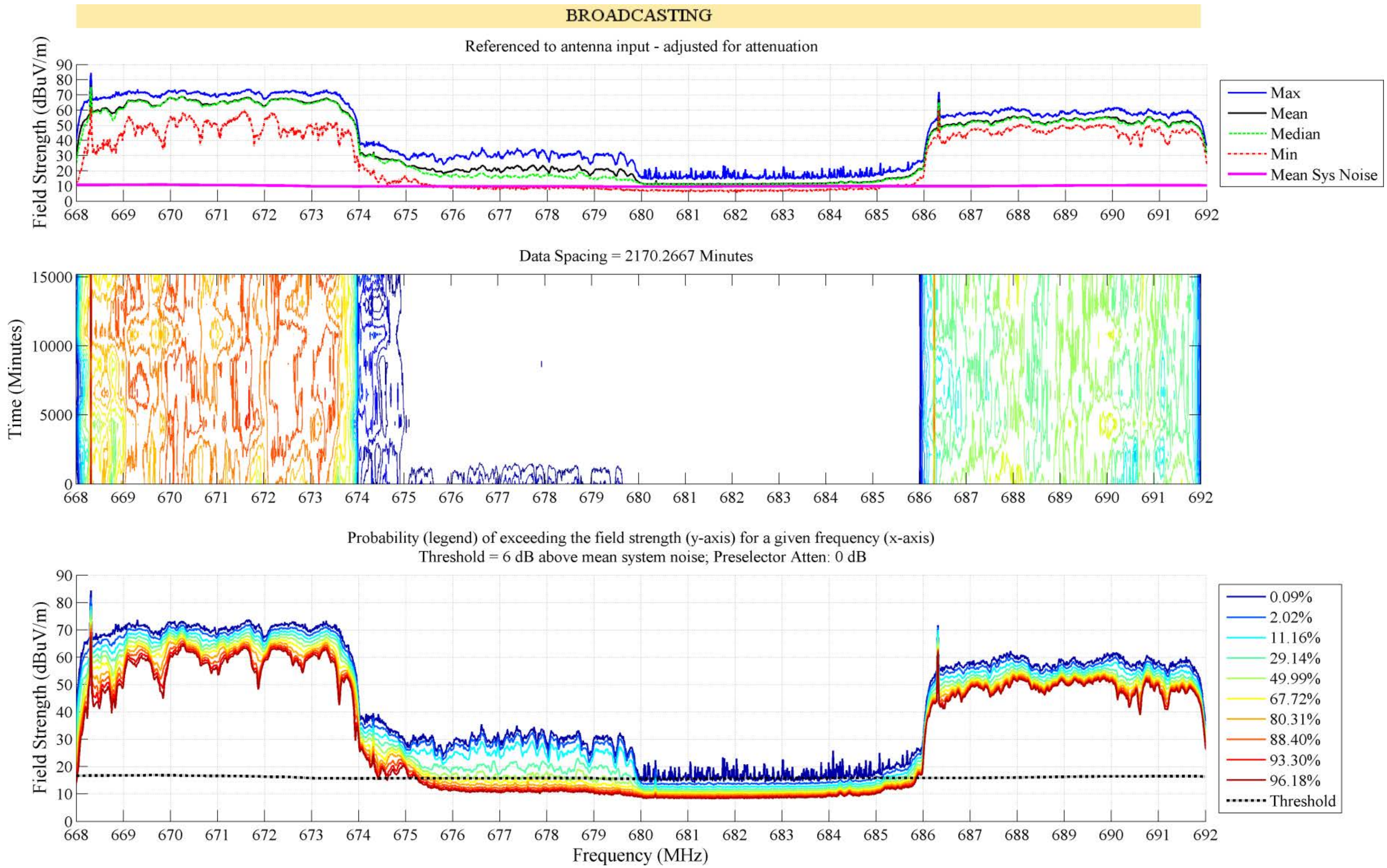

Figure 49. NTIA spectrum survey results from 668 to 692 MHz in Chicago, IL, September 2012.

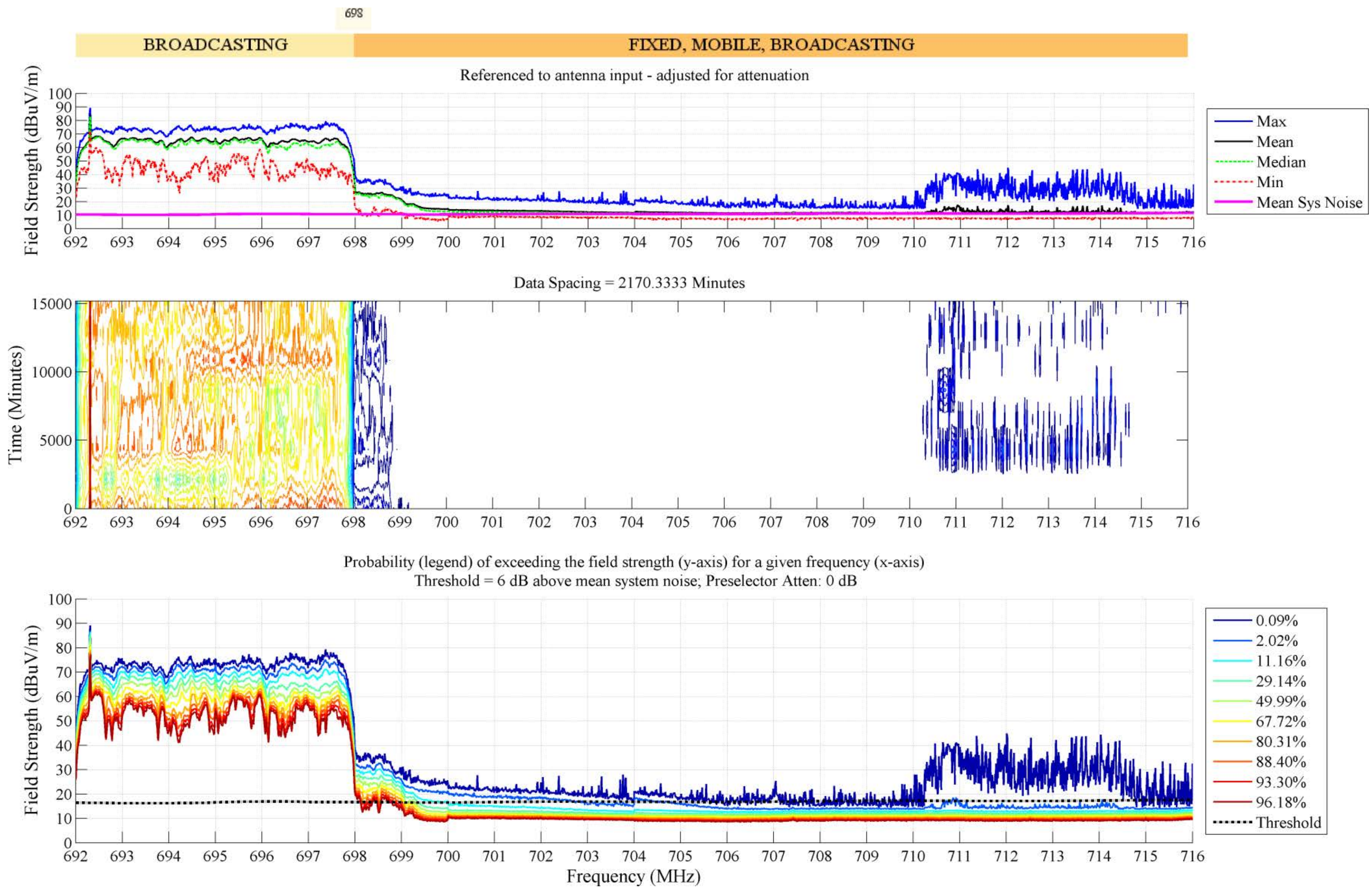

Figure 50. NTIA spectrum survey results from 692 to 716 MHz in Chicago, IL, September 2012.

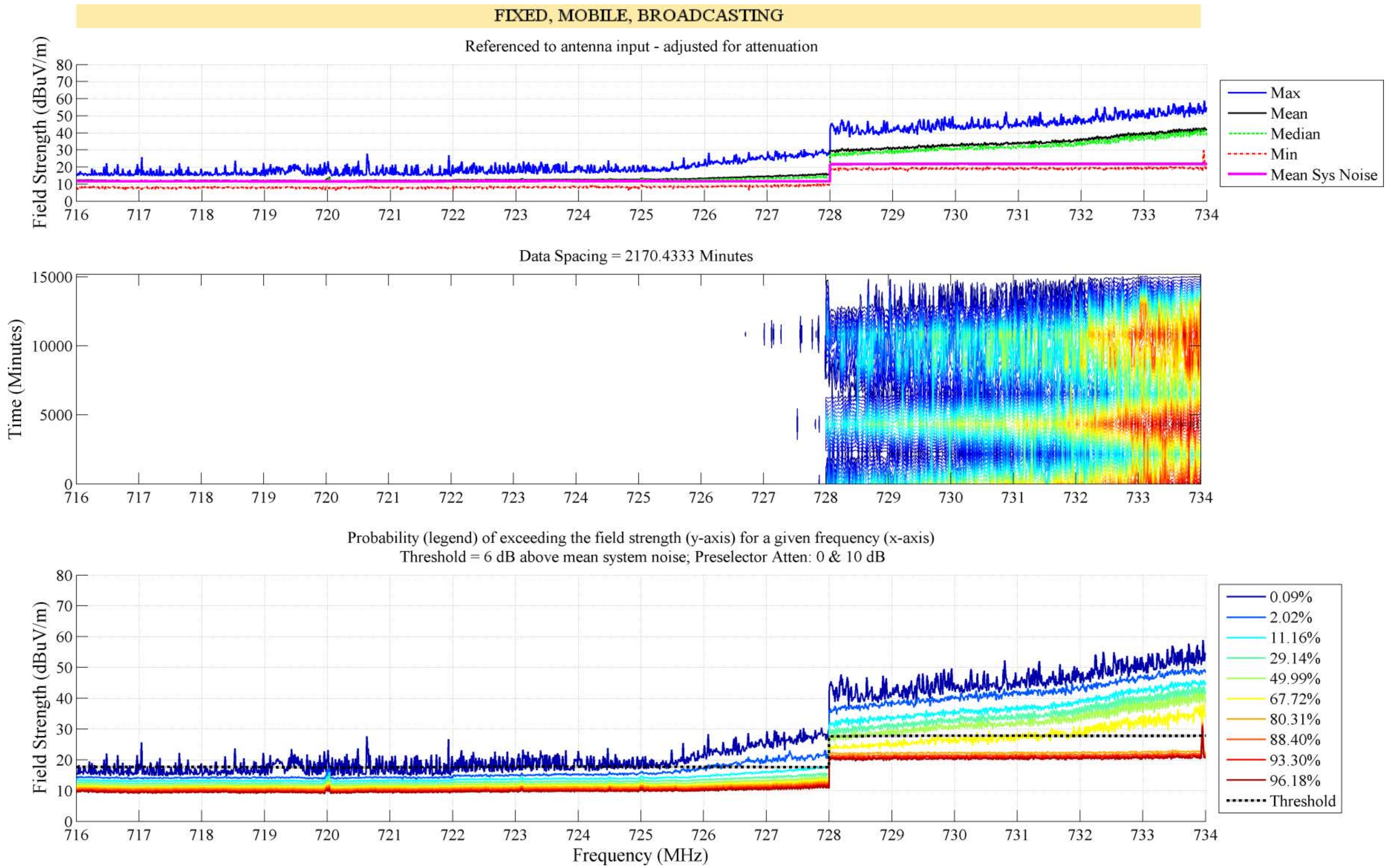

Figure 51. NTIA spectrum survey results from 716 to 734 MHz in Chicago, IL, September 2012.

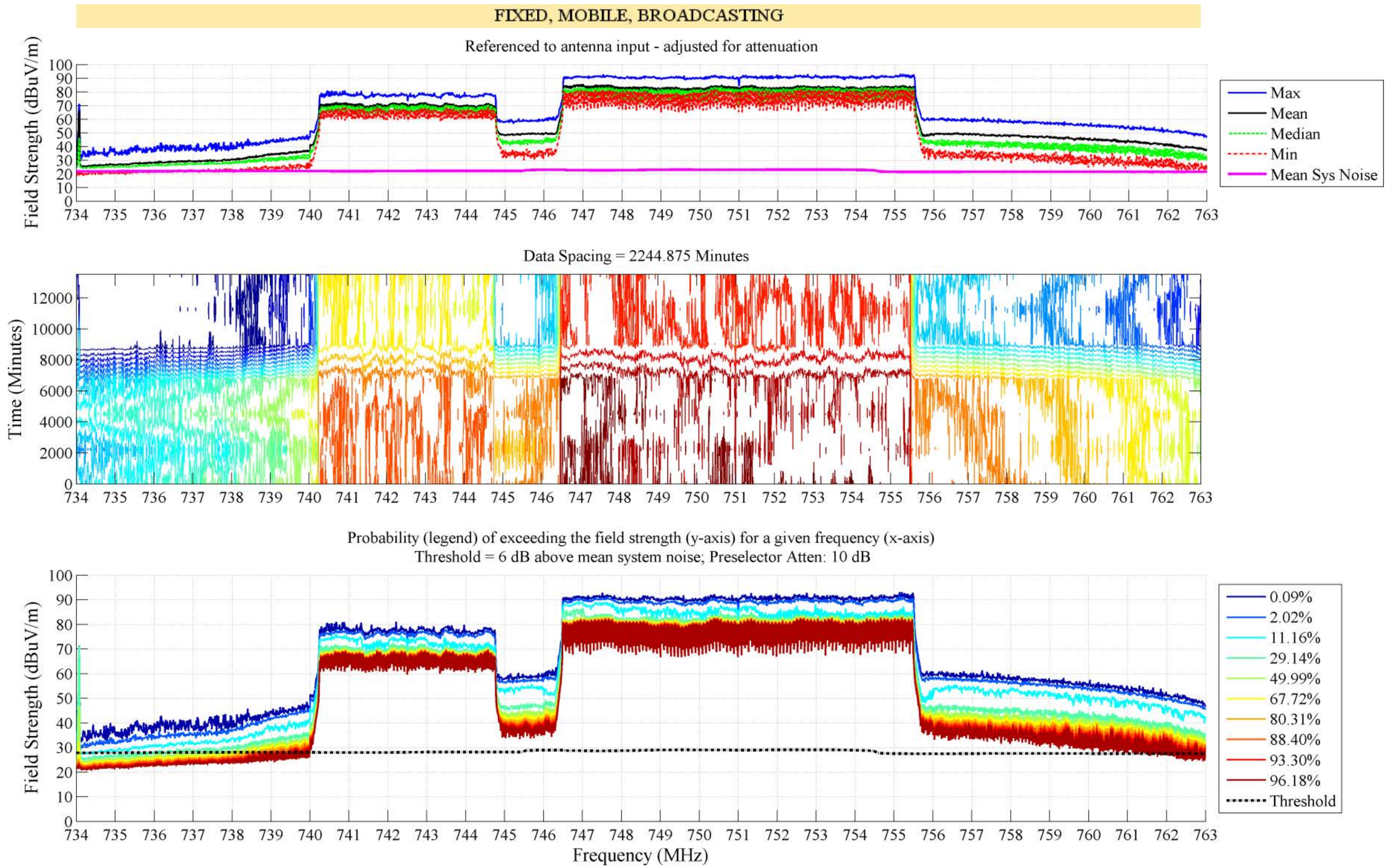

Figure 52. NTIA spectrum survey results from 734 to 763 MHz in Chicago, IL, September 2012.

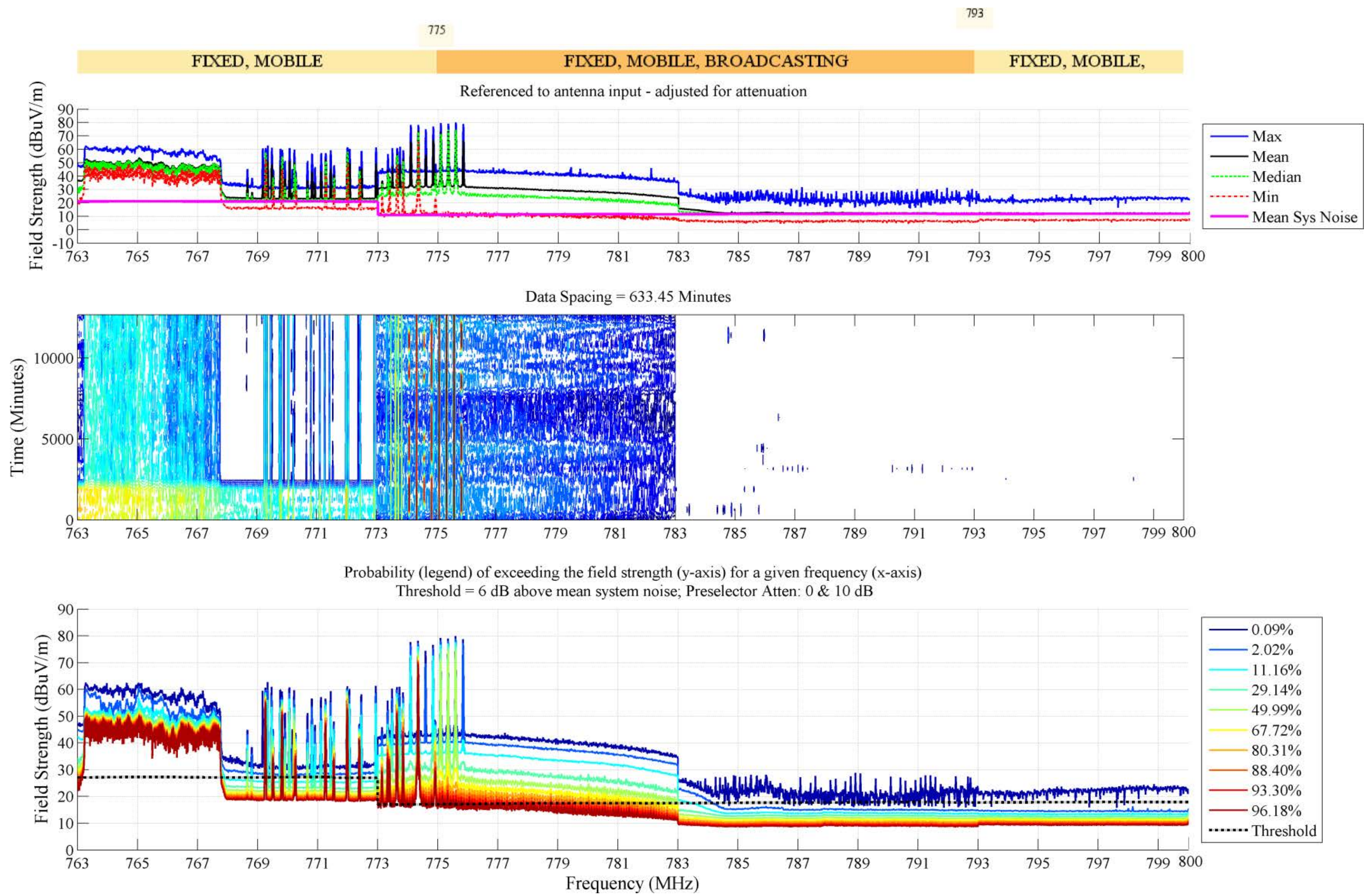

Figure 53. NTIA spectrum survey results from 763 to 800 MHz in Chicago, IL, September 2012.

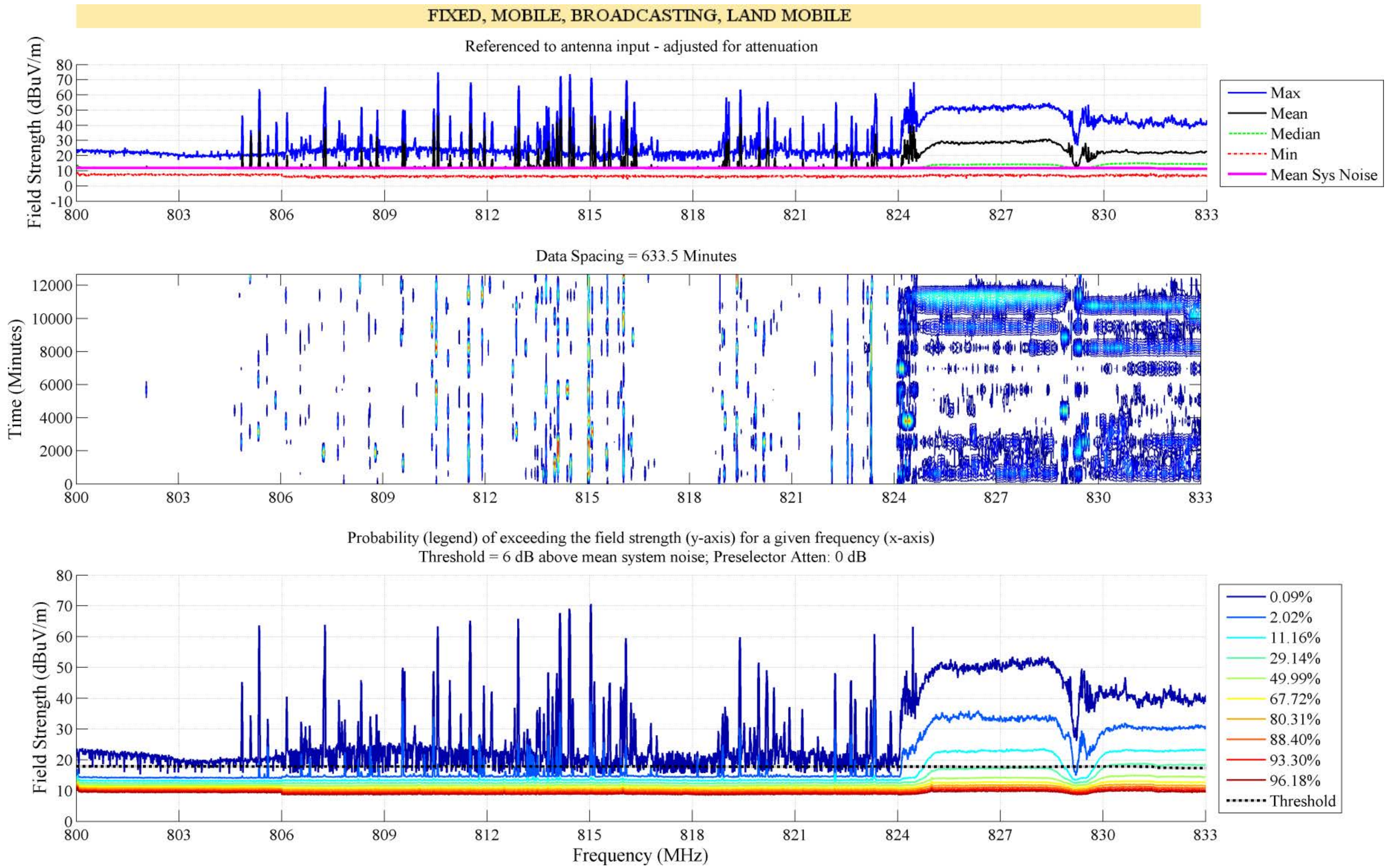

Figure 54. NTIA spectrum survey results from 800 to 833 MHz in Chicago, IL, September 2012.

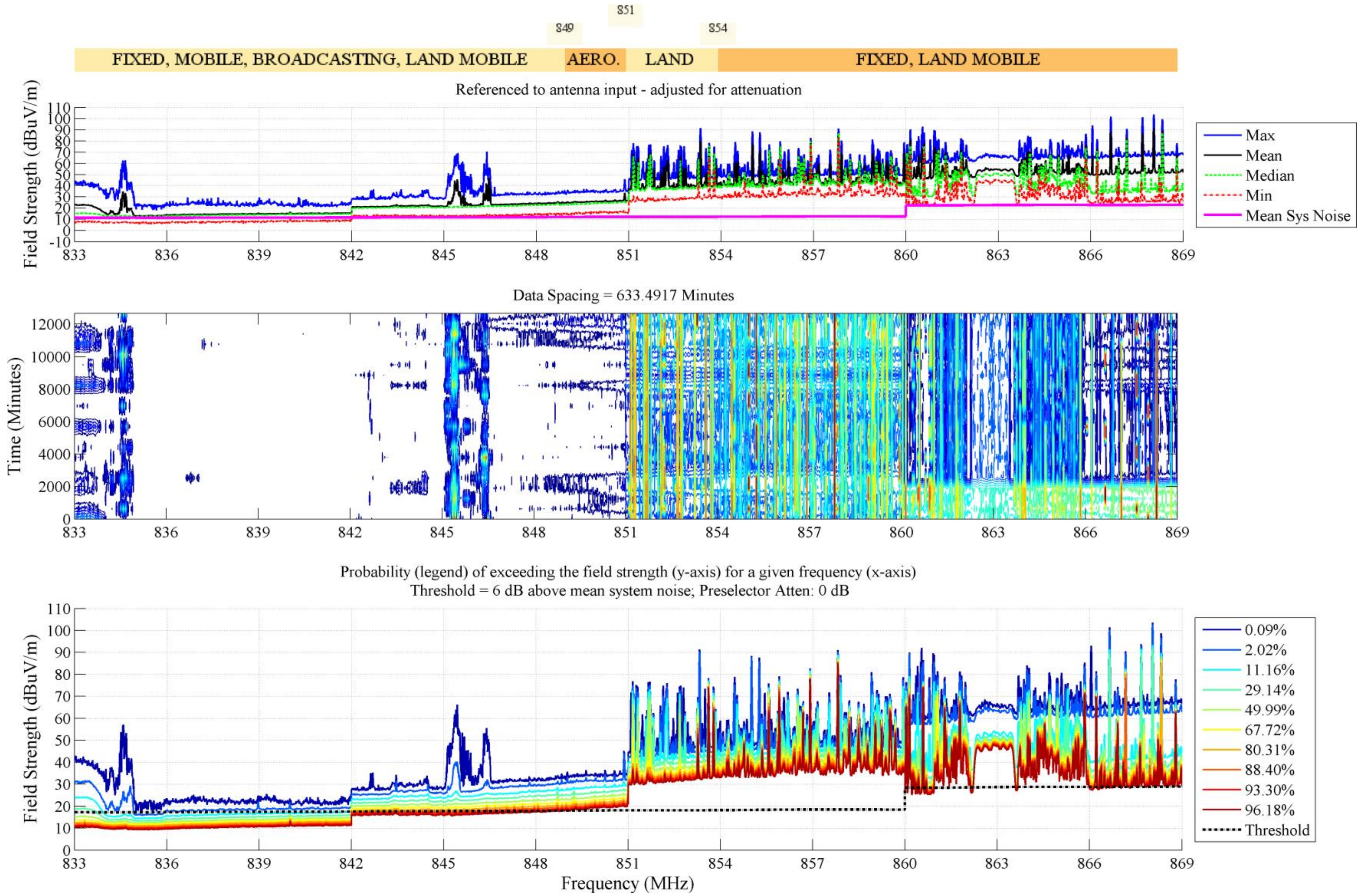

Figure 55. NTIA spectrum survey results from 833 to 869 MHz in Chicago, IL, September 2012.

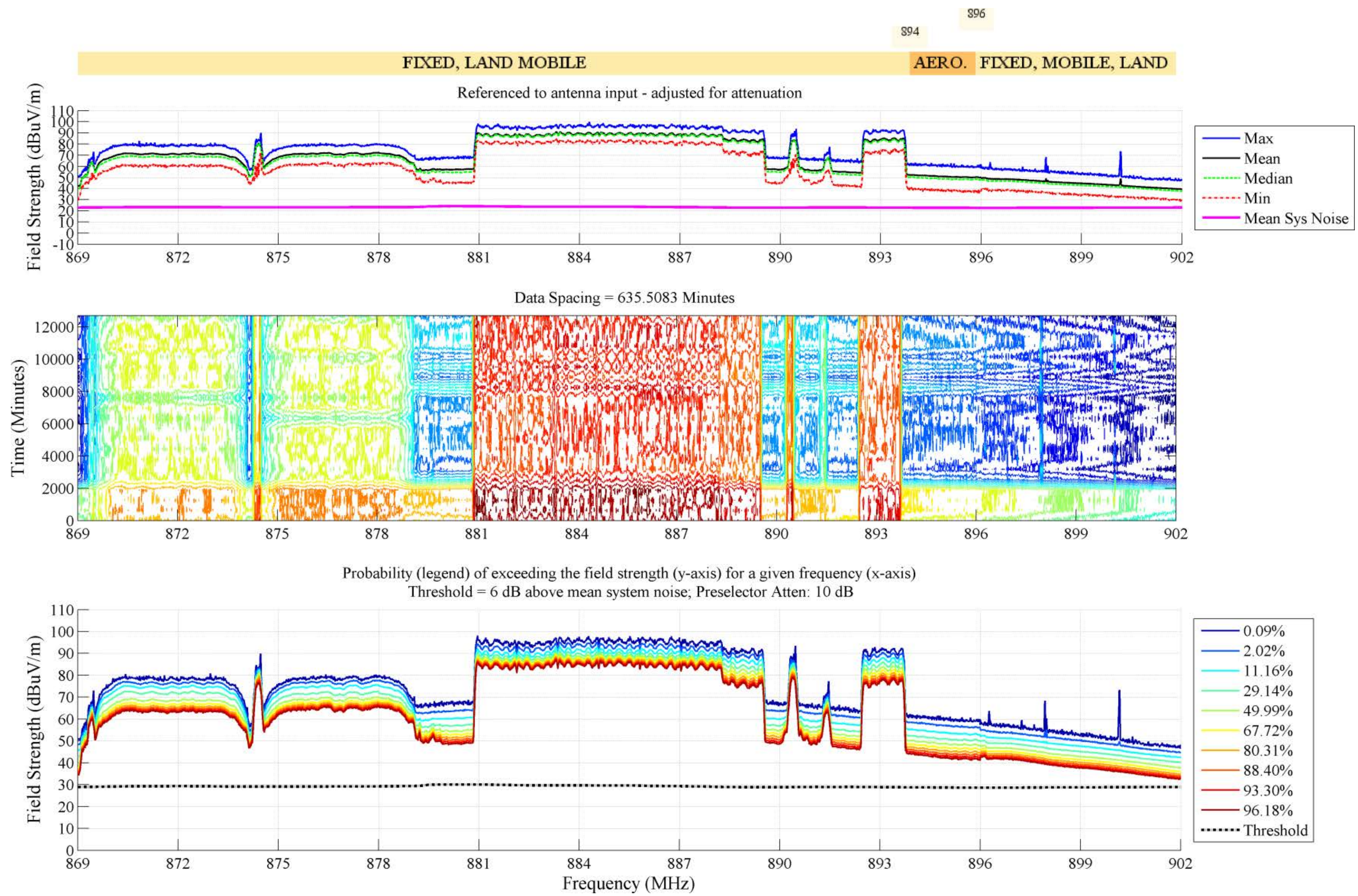

Figure 56. NTIA spectrum survey results from 869 to 902 MHz in Chicago, IL, September 2012.

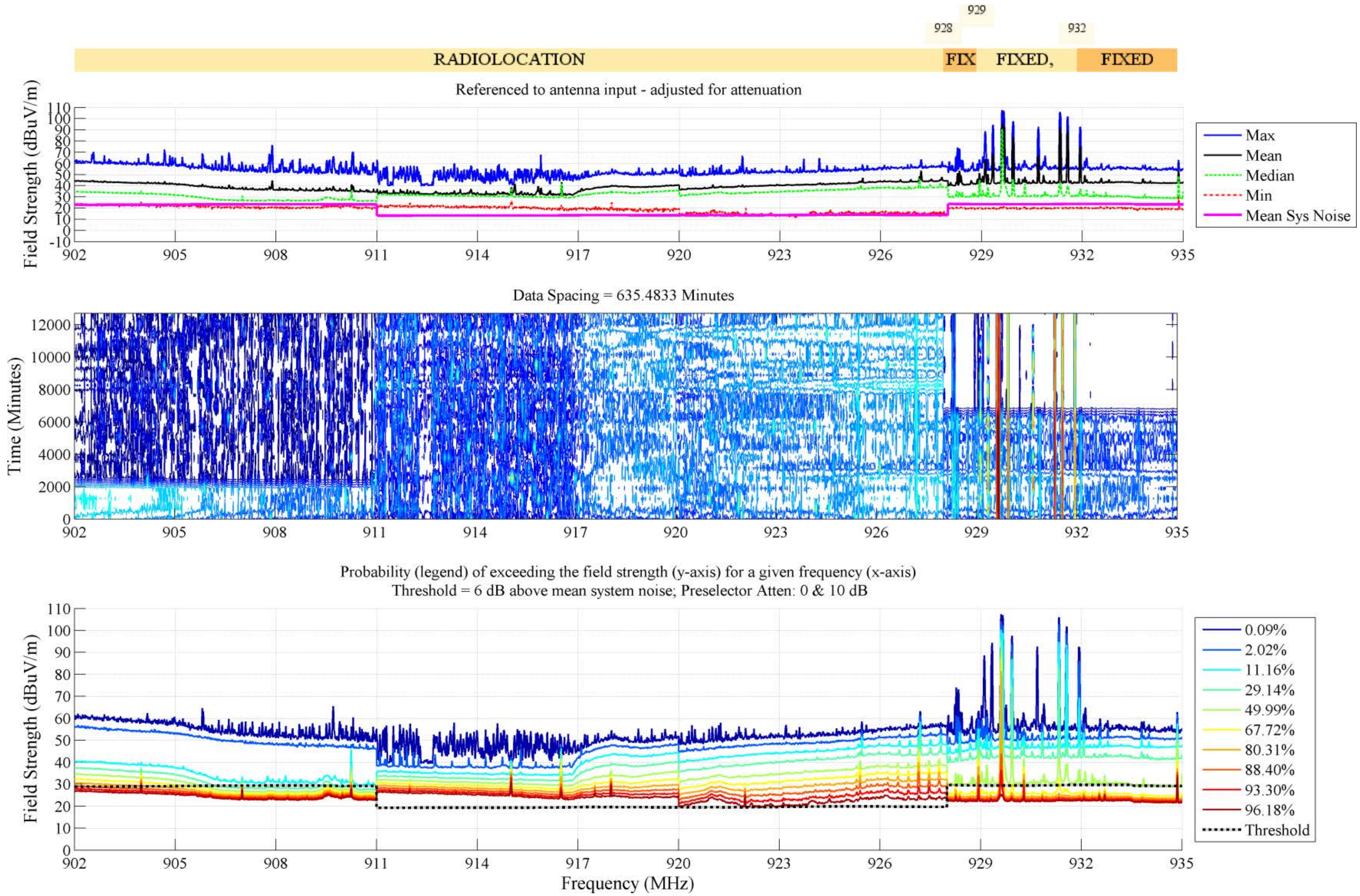

Figure 57. NTIA spectrum survey results from 902 to 935 MHz in Chicago, IL, September 2012.

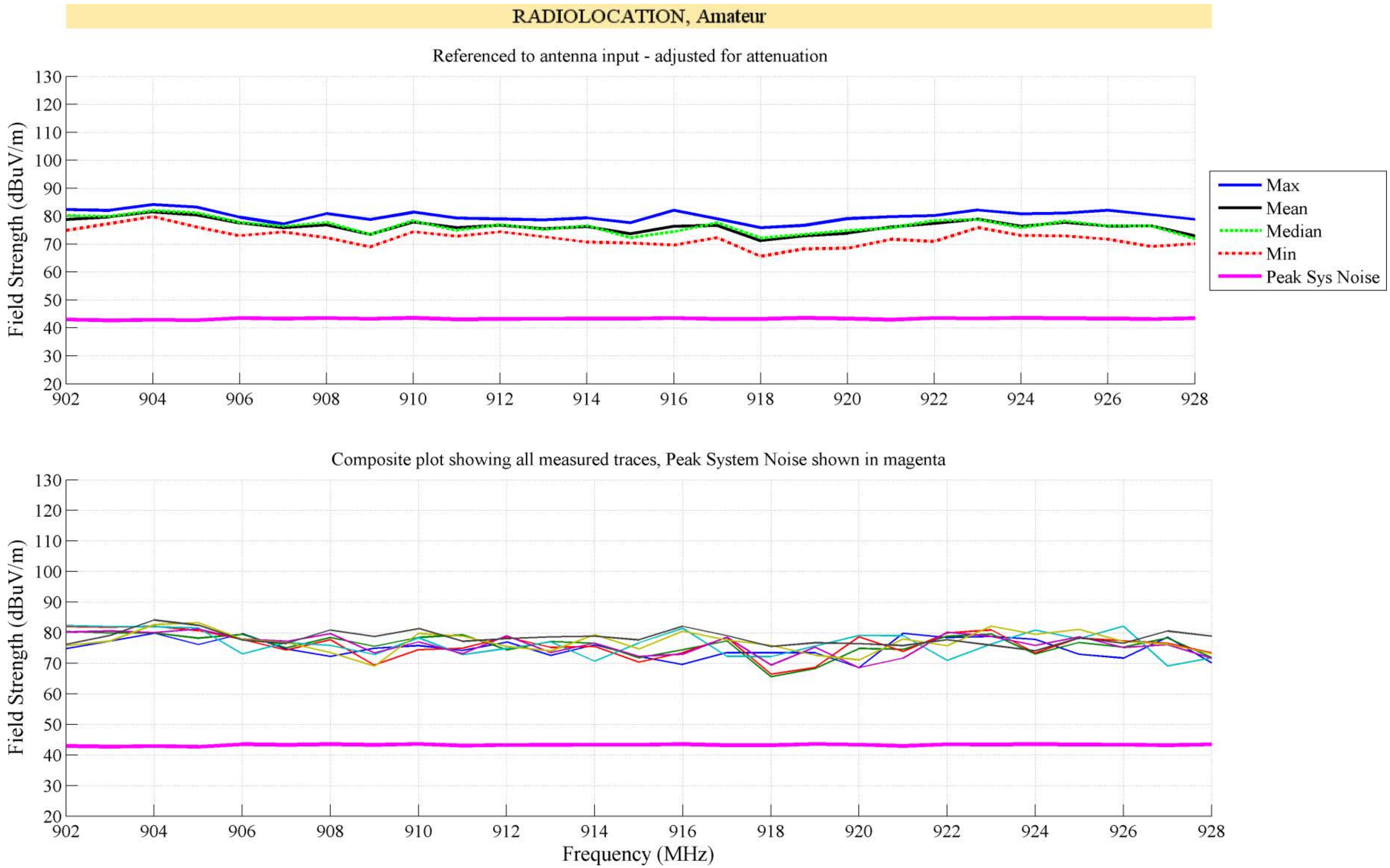

Figure 58. NTIA spectrum survey results from 902 to 928 MHz in Chicago, IL, September 2012. This measurement was taken using the stepped-spectrum measurement algorithm.

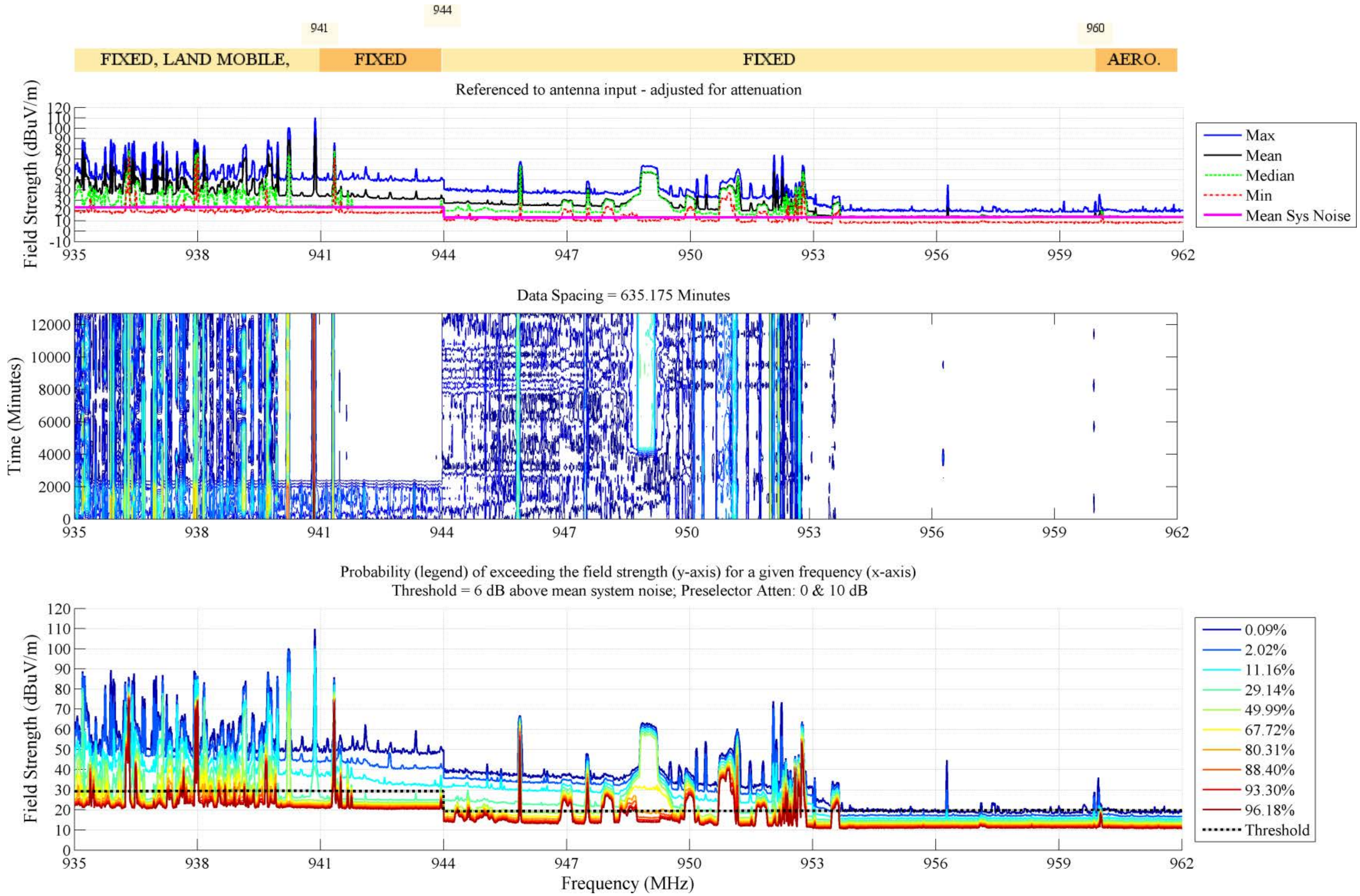

Figure 59. NTIA spectrum survey results from 935 to 962 MHz in Chicago, IL, September 2012.

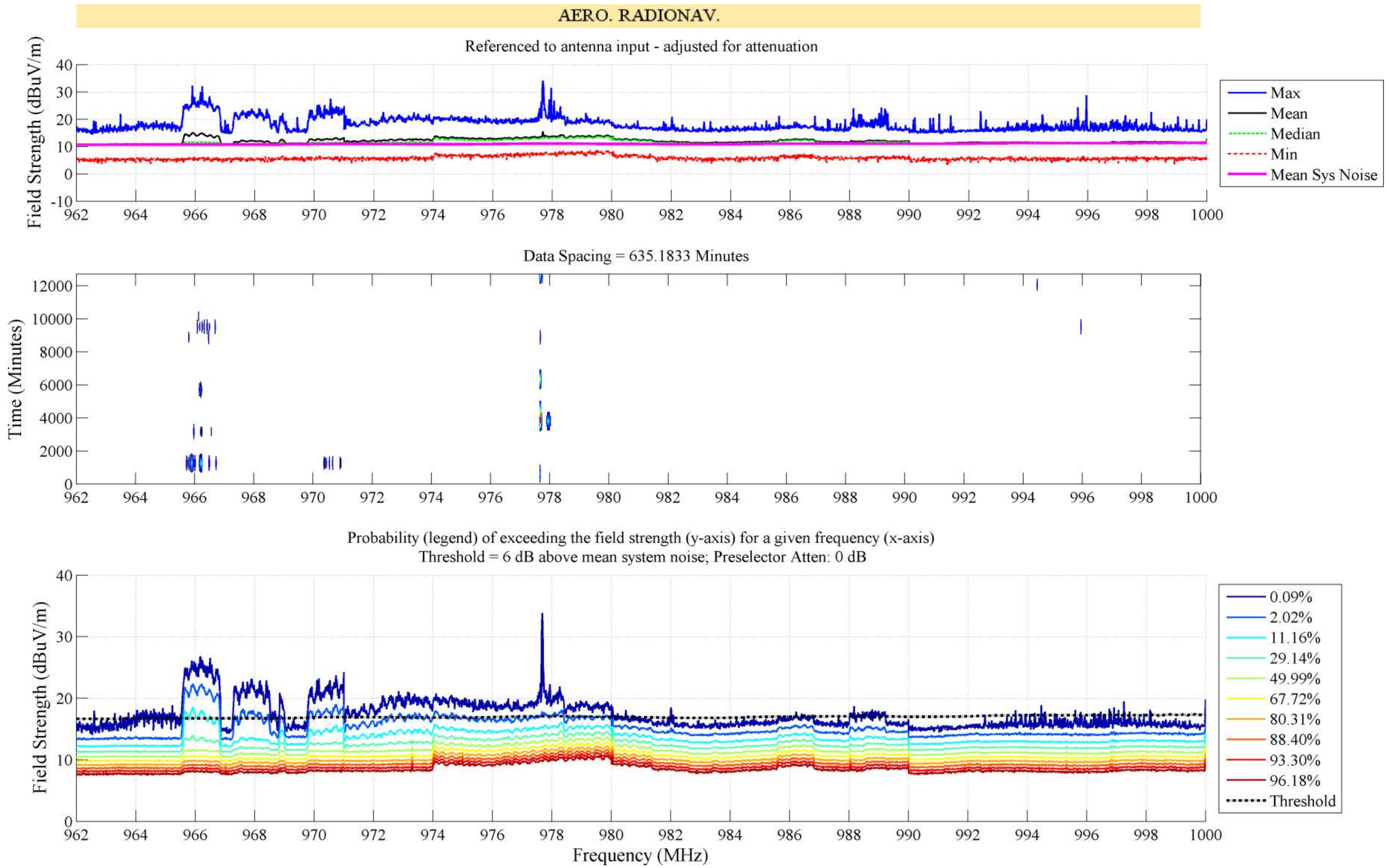

Figure 60. NTIA spectrum survey results from 962 to 1000 MHz in Chicago, IL, September 2012.

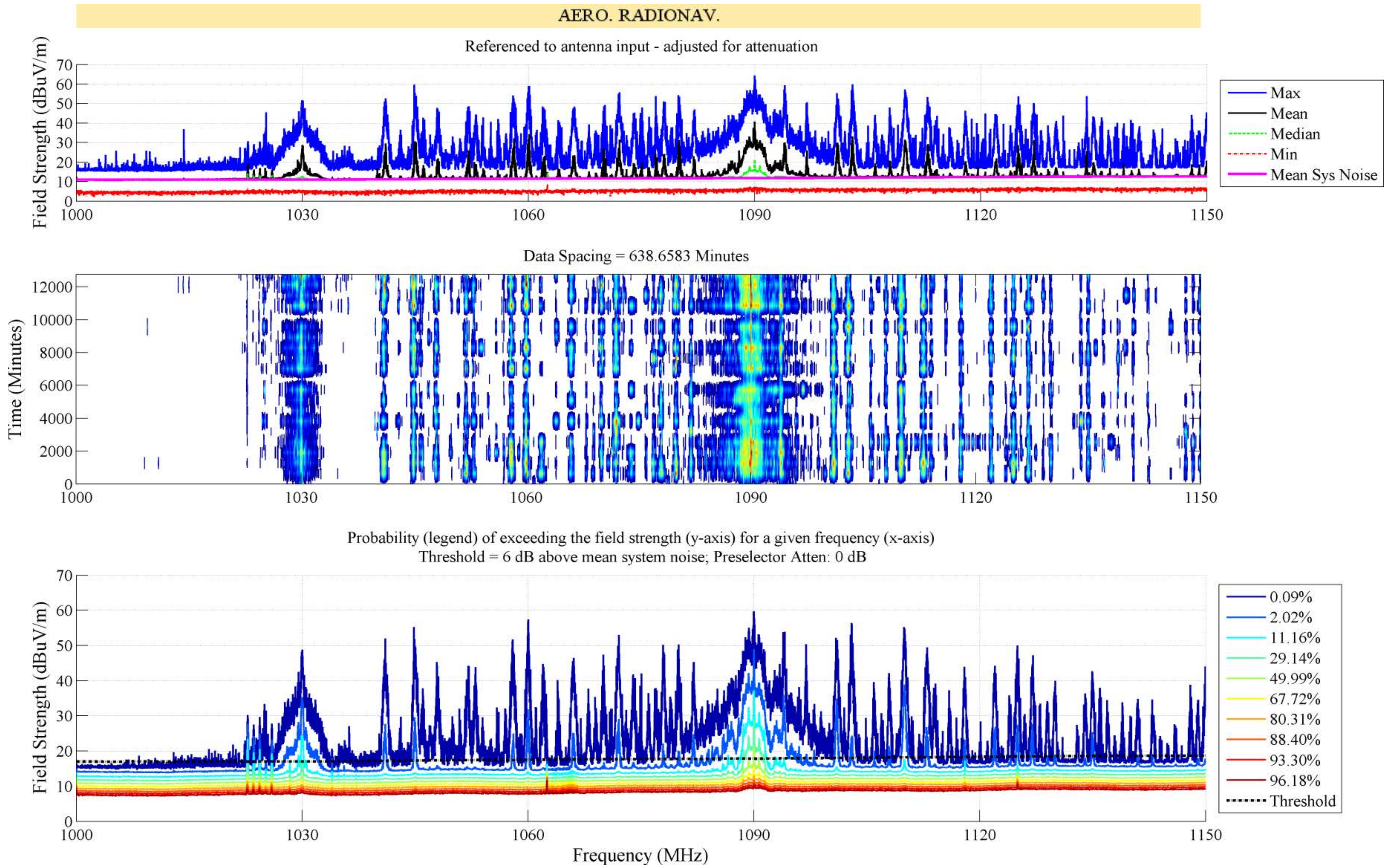

Figure 61. NTIA spectrum survey results from 1000 to 1150 MHz in Chicago, IL, September 2012.

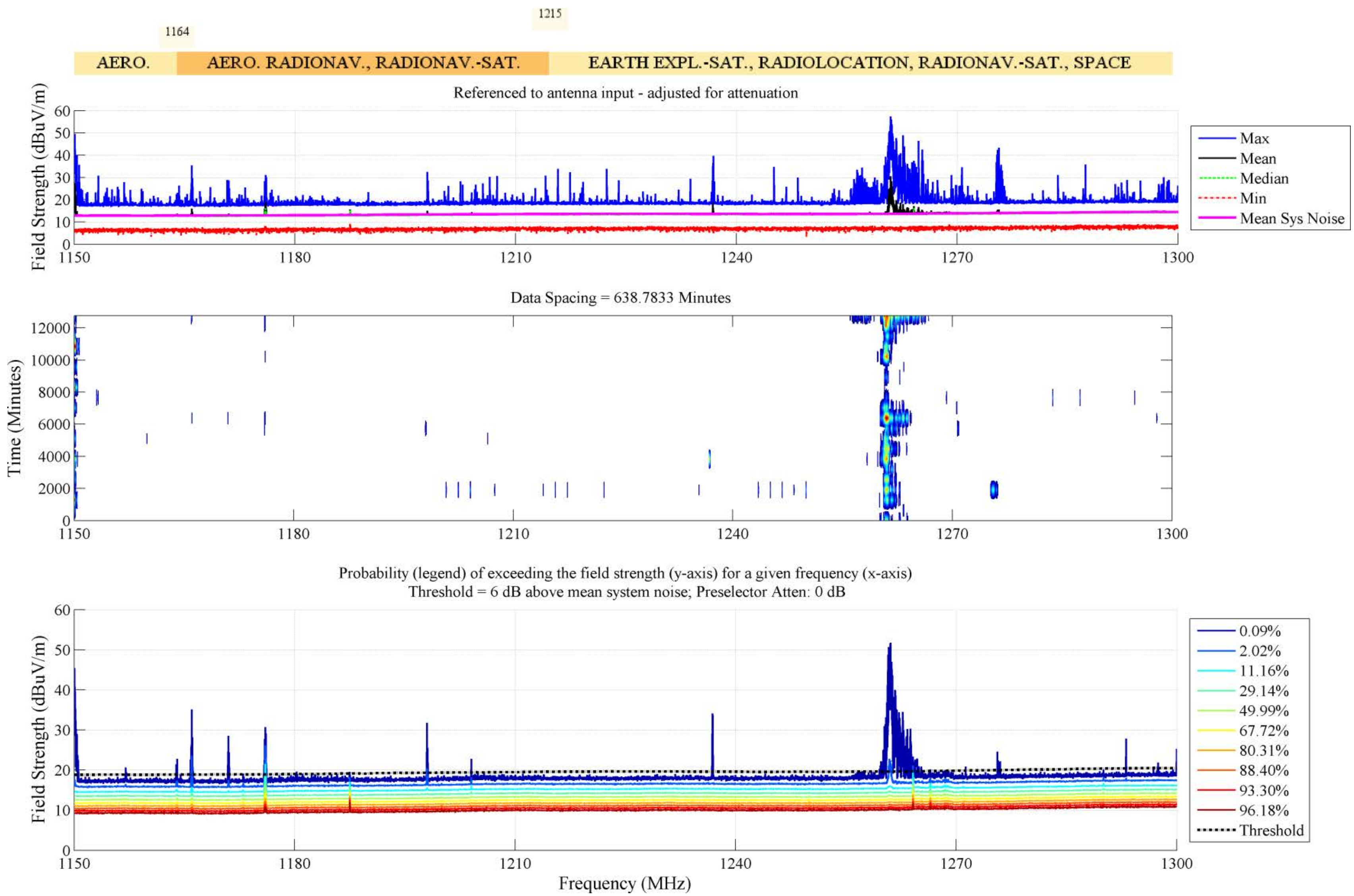

Figure 62. NTIA spectrum survey results from 1150 to 1300 MHz in Chicago, IL, September 2012.

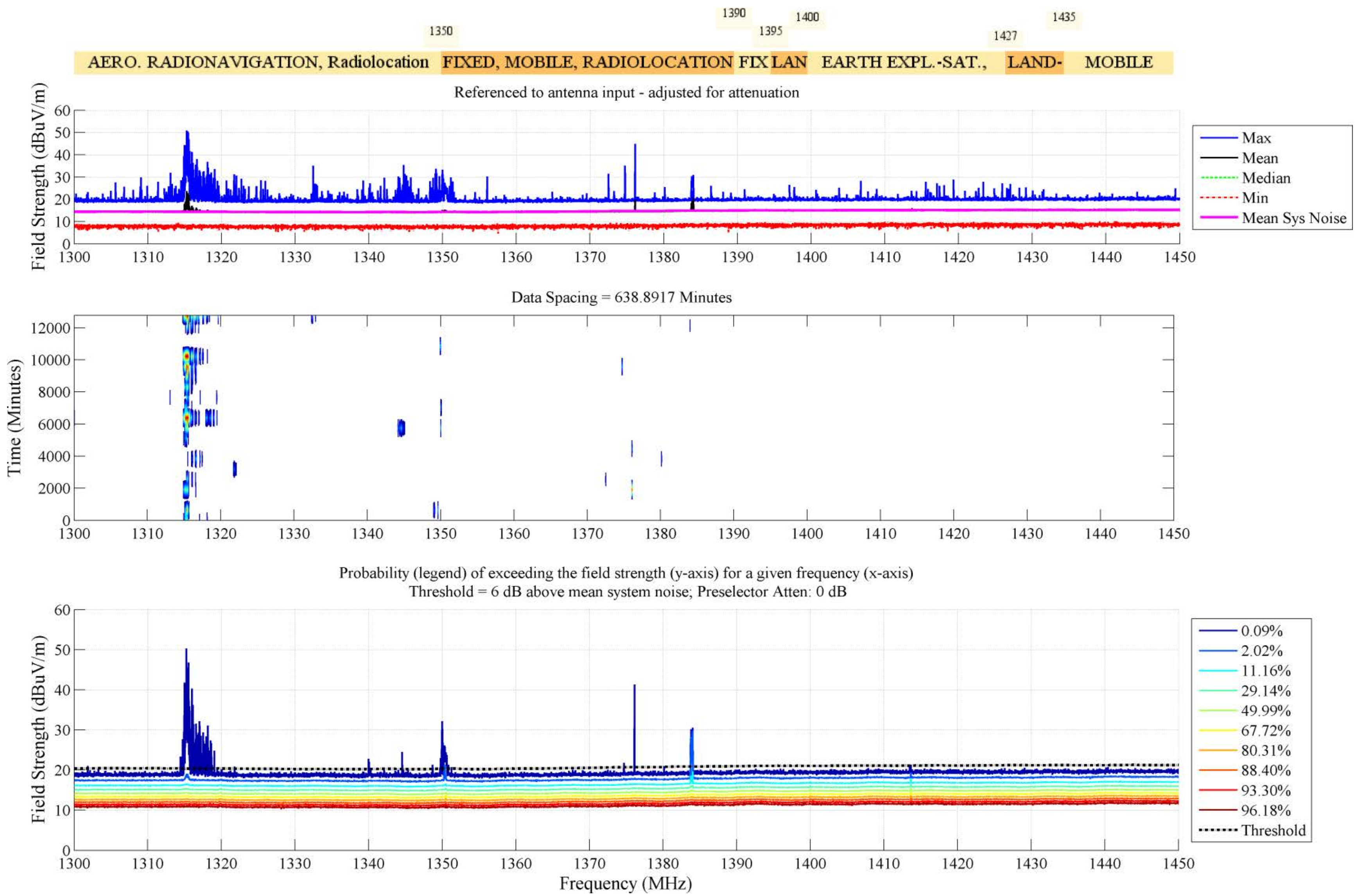

Figure 63. NTIA spectrum survey results from 1300 to 1450 MHz in Chicago, IL, September 2012.

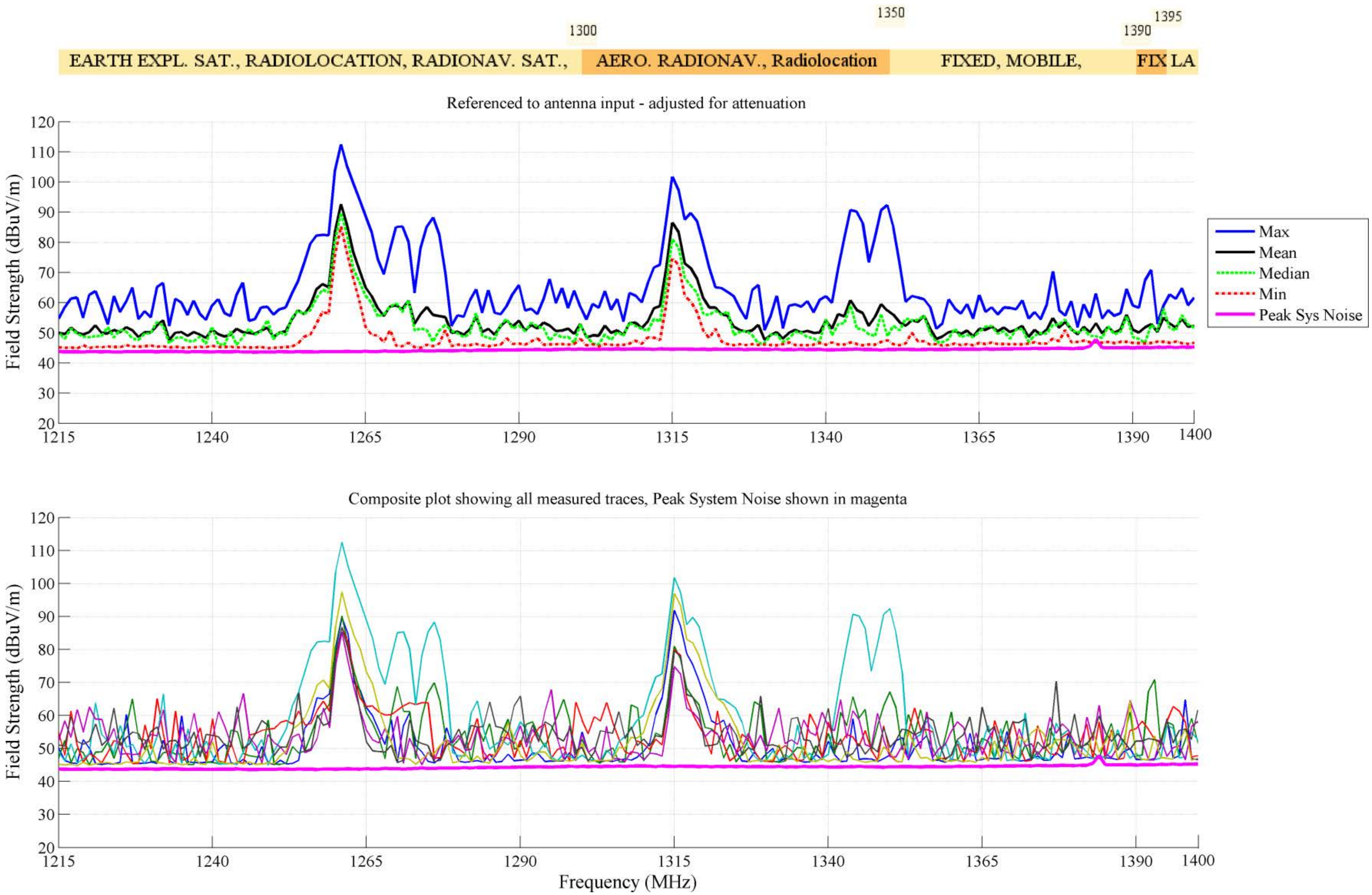

Figure 64. NTIA spectrum survey results from 1215 to 1400 MHz in Chicago, IL, September 2012. This measurement was taken using the stepped-spectrum measurement algorithm.

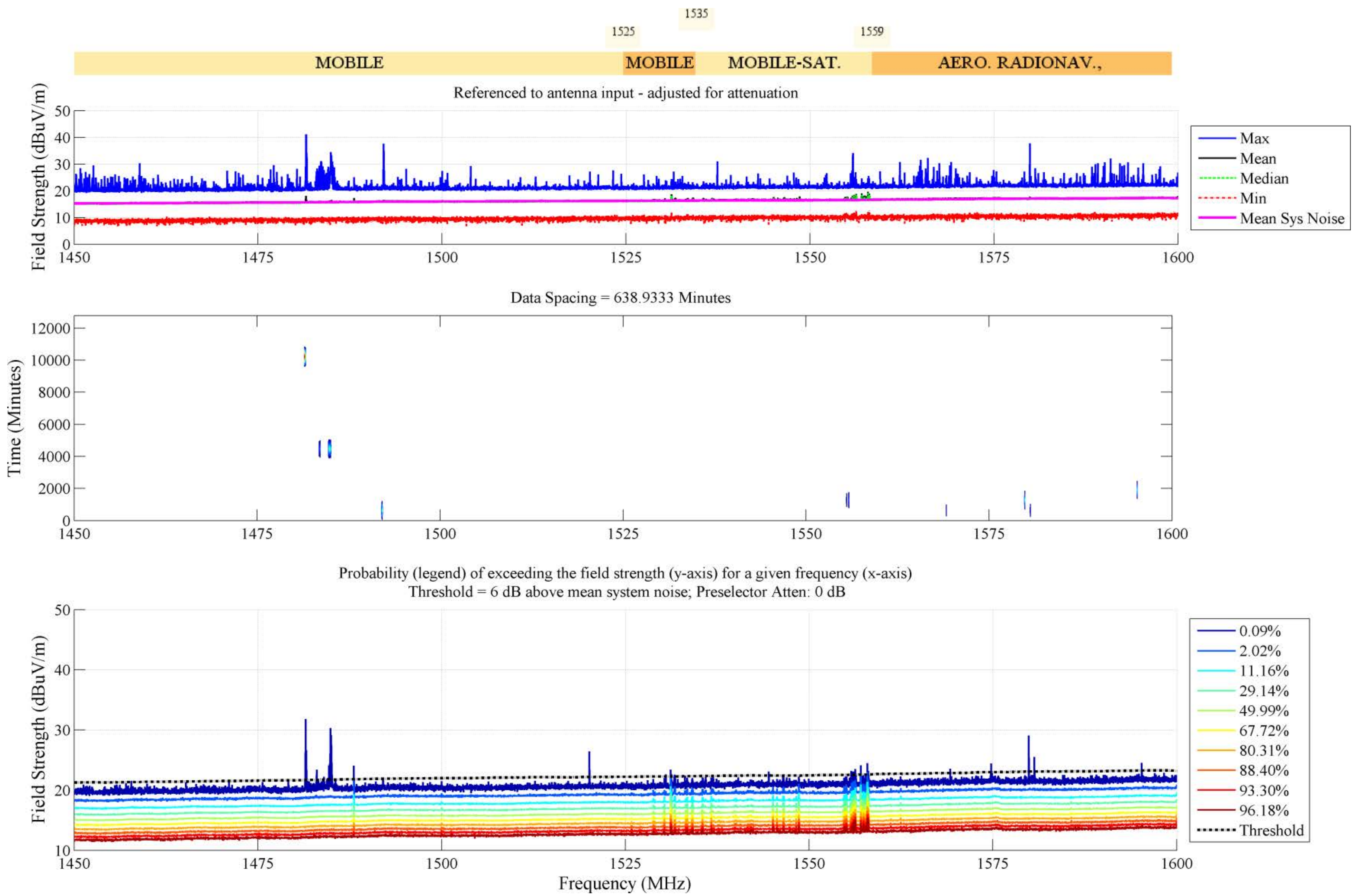

Figure 65. NTIA spectrum survey results from 1450 to 1600 MHz in Chicago, IL, September 2012.

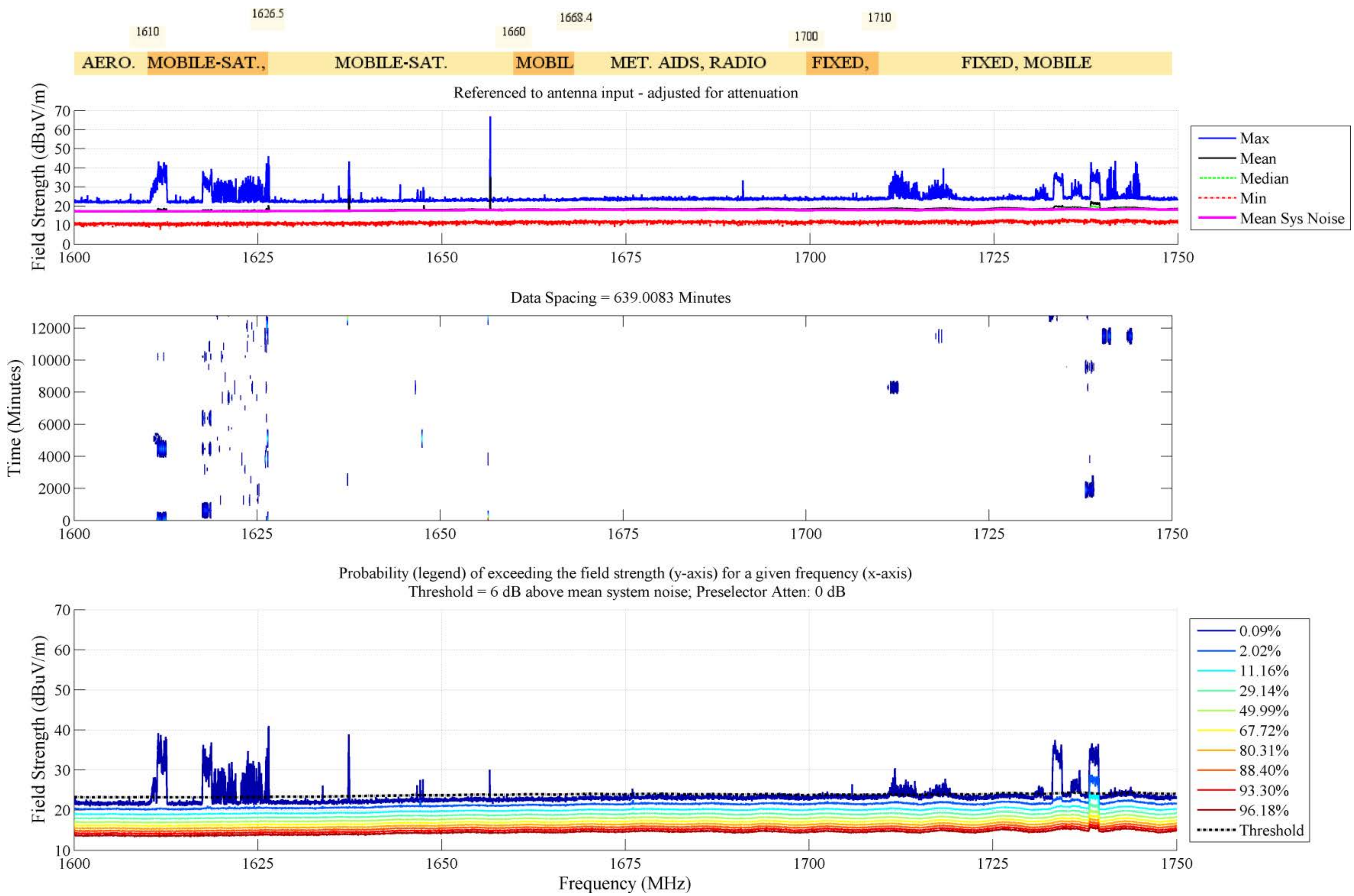

Figure 66. NTIA spectrum survey results from 1600 to 1750 MHz in Chicago, IL, September 2012.

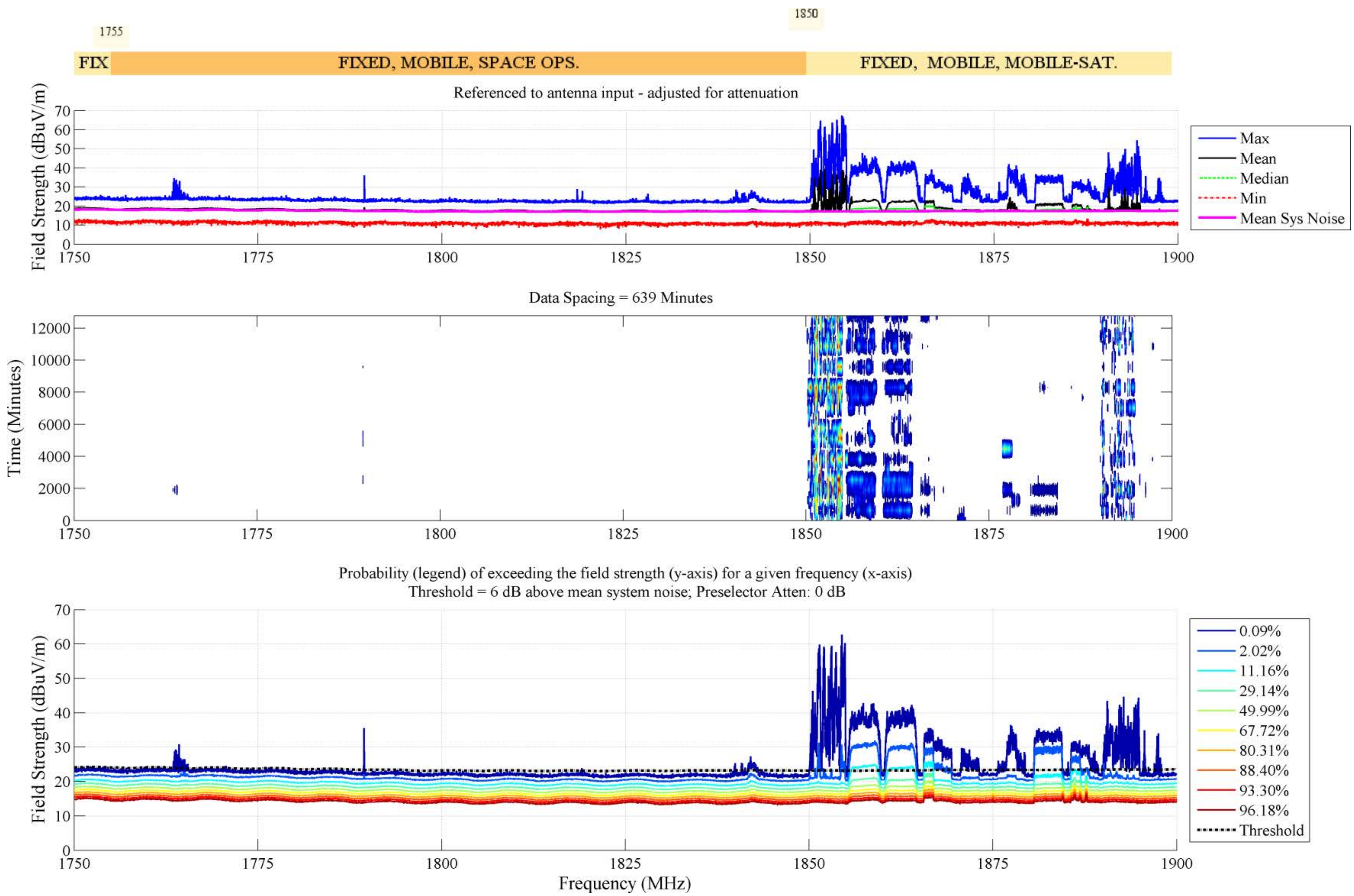

Figure 67. NTIA spectrum survey results from 1750 to 1900 MHz in Chicago, IL, September 2012.

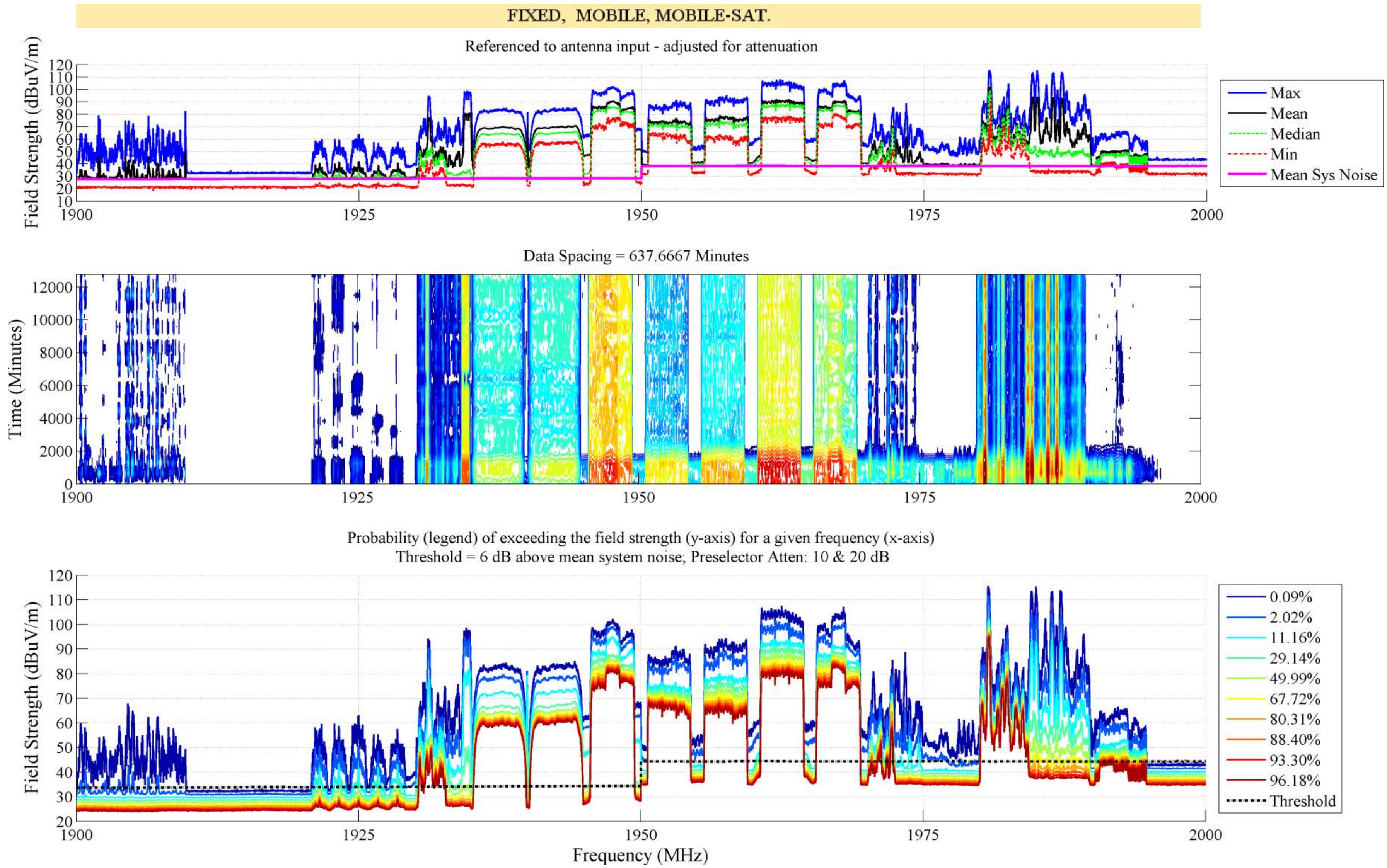

Figure 68. NTIA spectrum survey results from 1900 to 2000 MHz in Chicago, IL, September 2012.

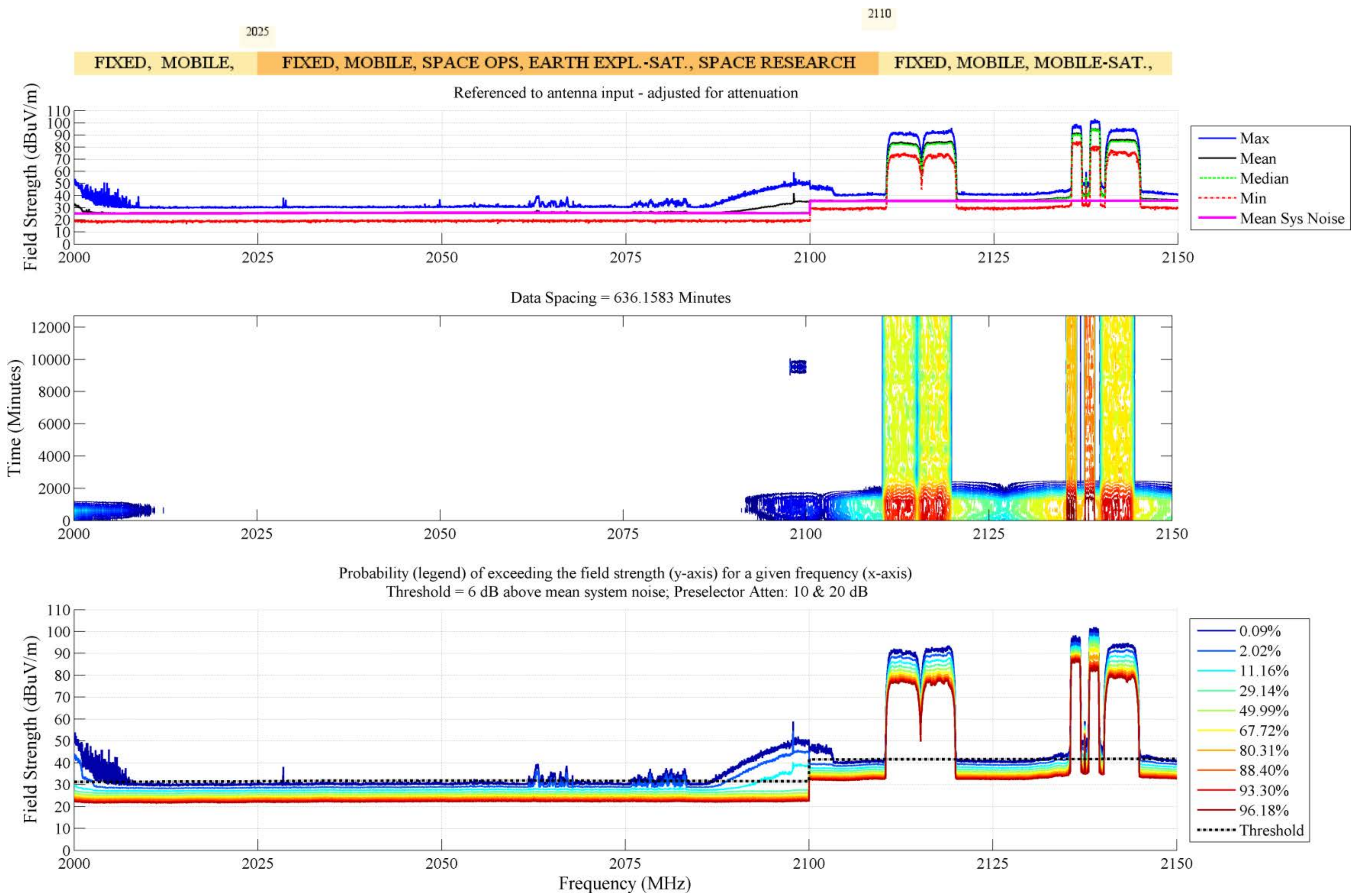

Figure 69. NTIA spectrum survey results from 2000 to 2150 MHz in Chicago, IL, September 2012.

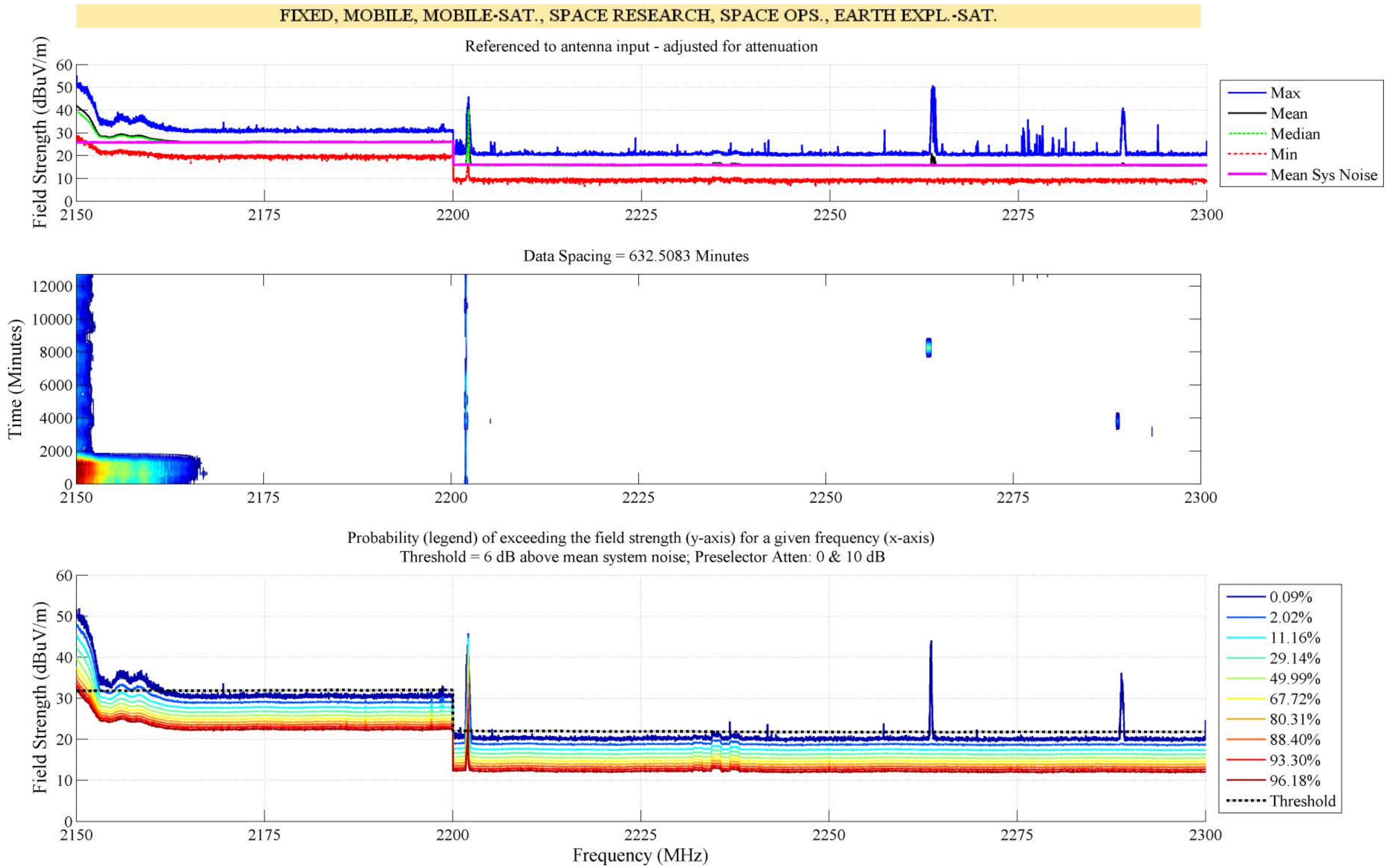

Figure 70. NTIA spectrum survey results from 2150 to 2300 MHz in Chicago, IL, September 2012.

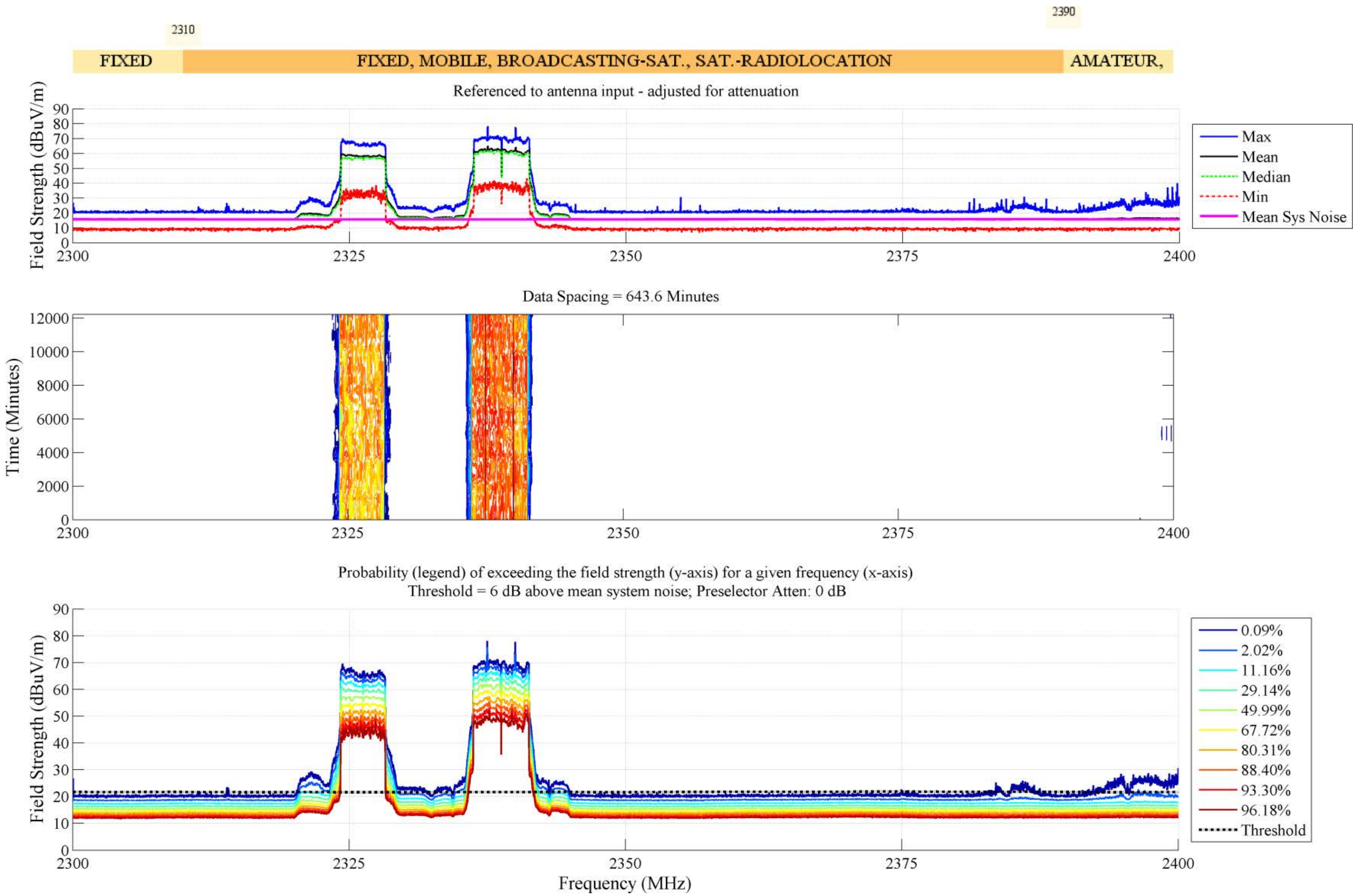

Figure 71. NTIA spectrum survey results from 2300 to 2400 MHz in Chicago, IL, September 2012.

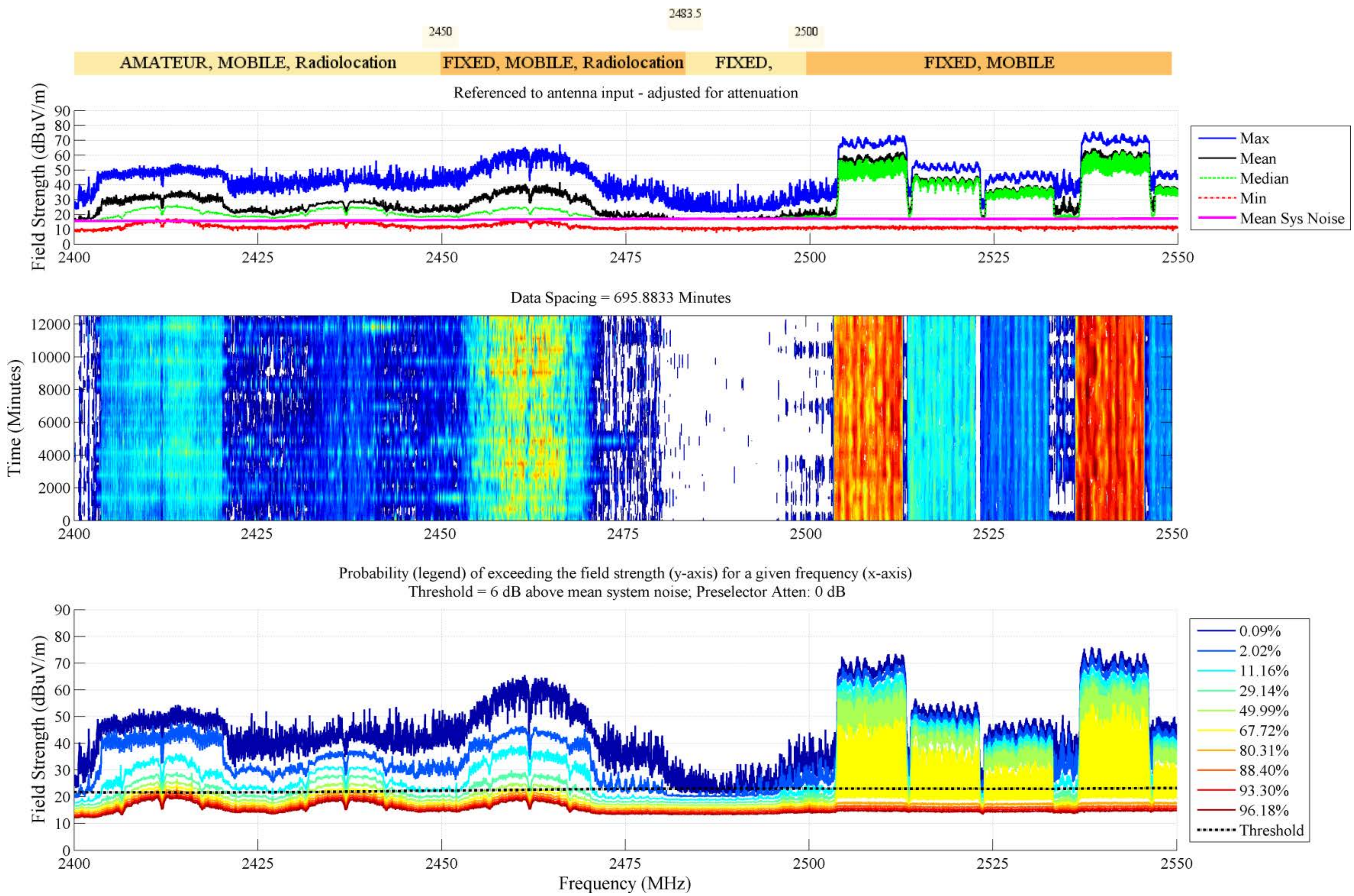

Figure 72. NTIA spectrum survey results from 2400 to 2550 MHz in Chicago, IL, September 2012.

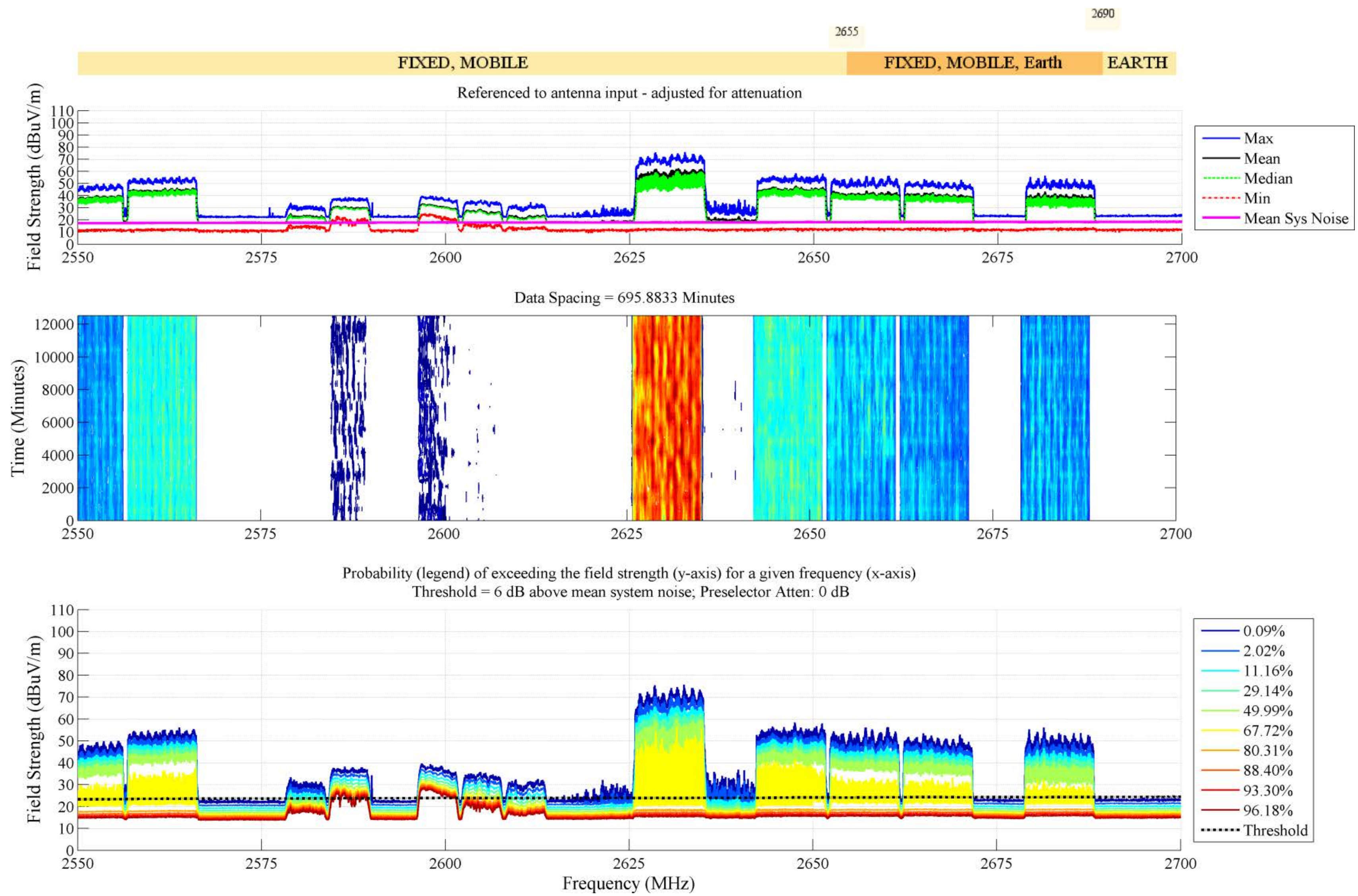

Figure 73. NTIA spectrum survey results from 2550 to 2700 MHz in Chicago, IL, September 2012.

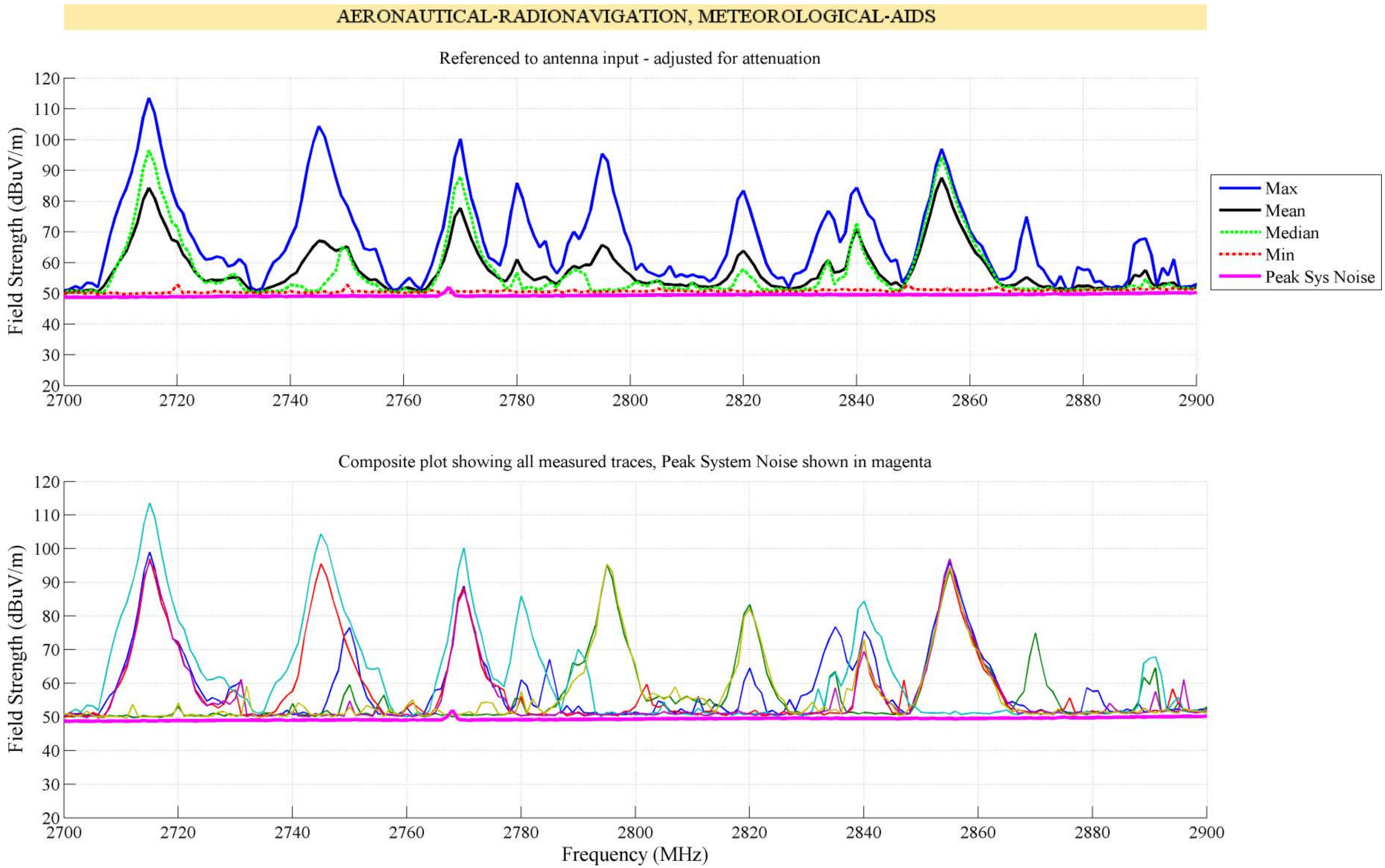

Figure 74. NTIA spectrum survey results from 2700 to 2900 MHz in Chicago, IL, September 2012. This measurement was taken using the stepped-spectrum measurement algorithm.

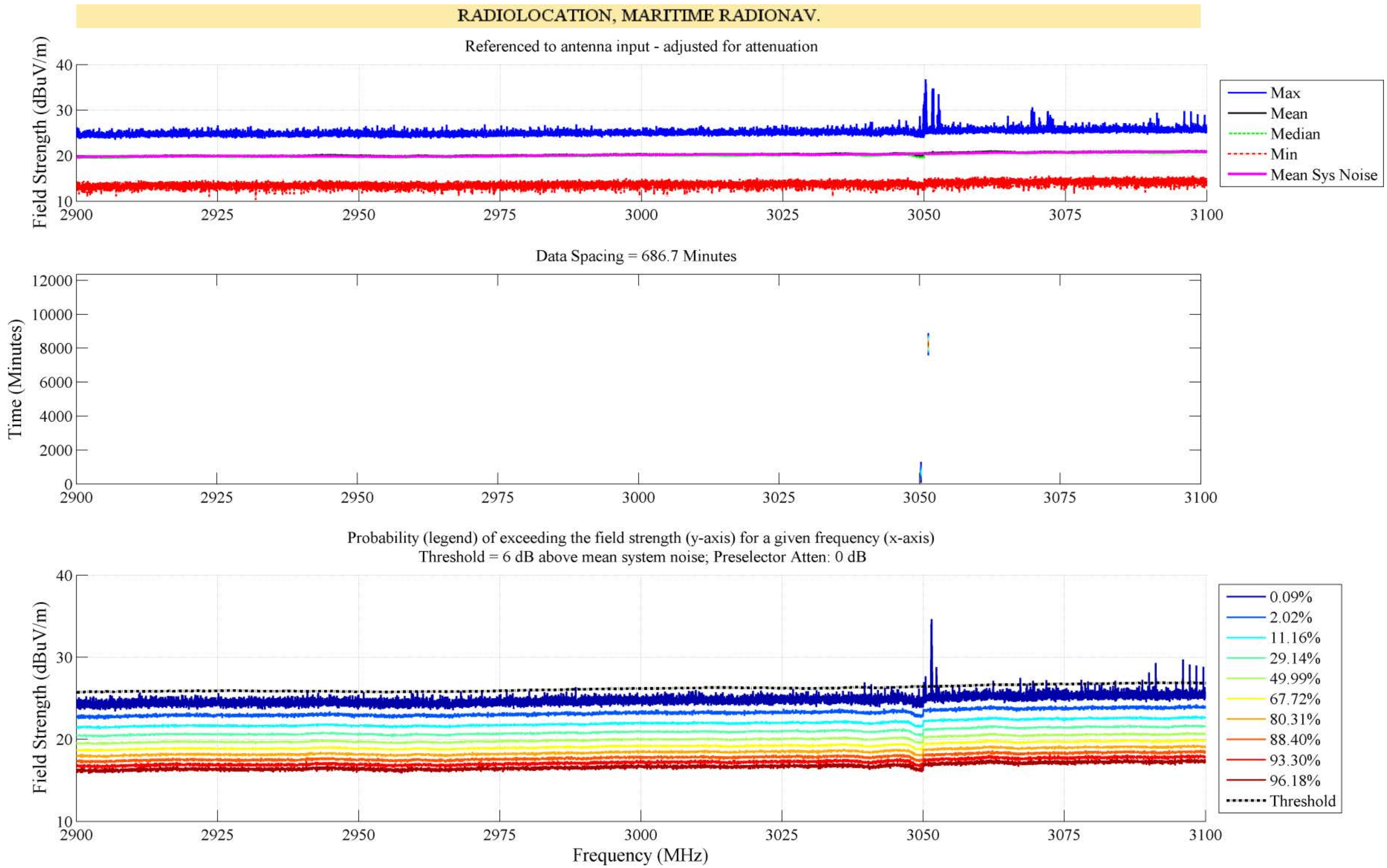

Figure 75. NTIA spectrum survey results from 2900 to 3100 MHz in Chicago, IL, September 2012.

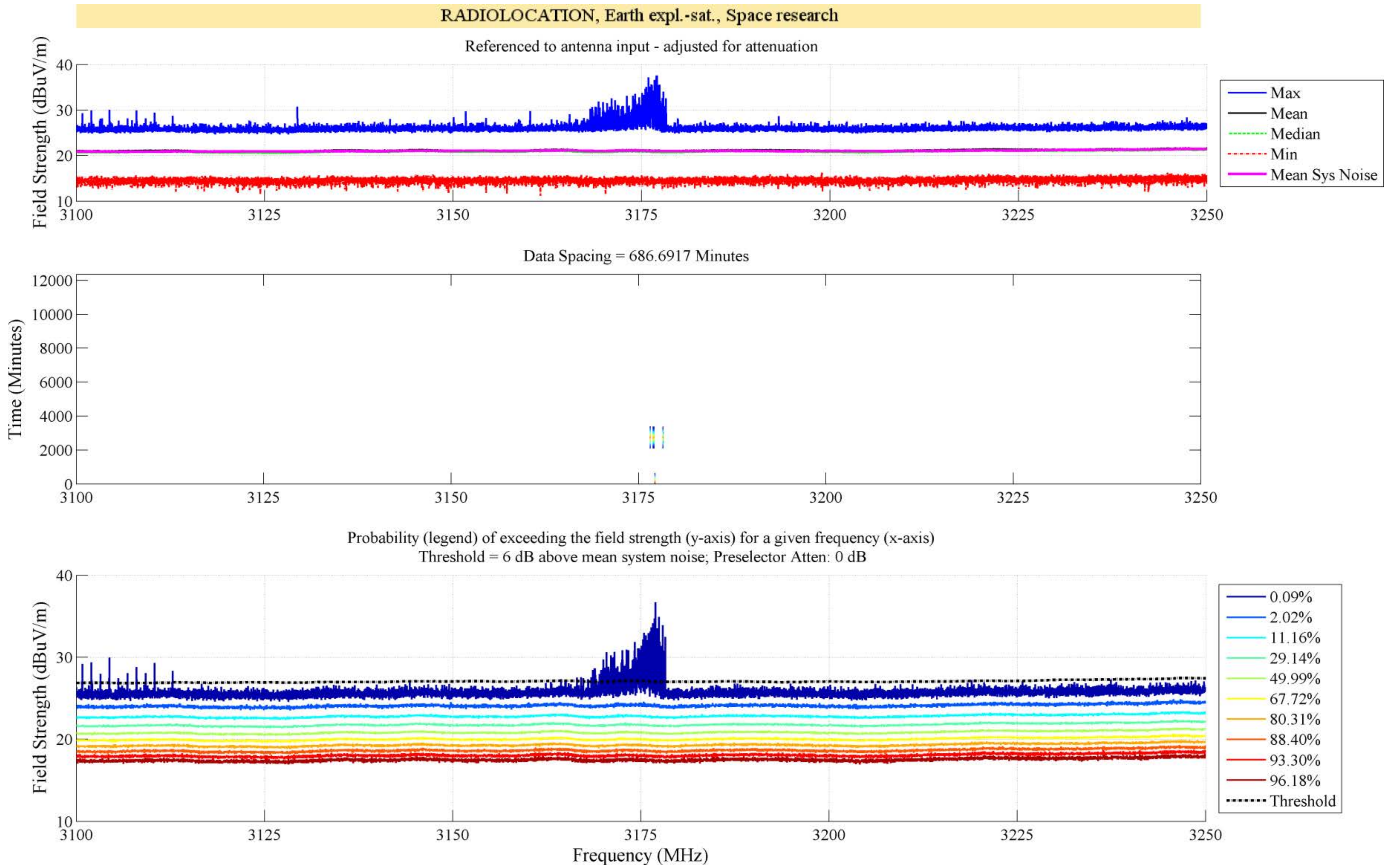

Figure 76. NTIA spectrum survey results from 3100 to 3250 MHz in Chicago, IL, September 2012.

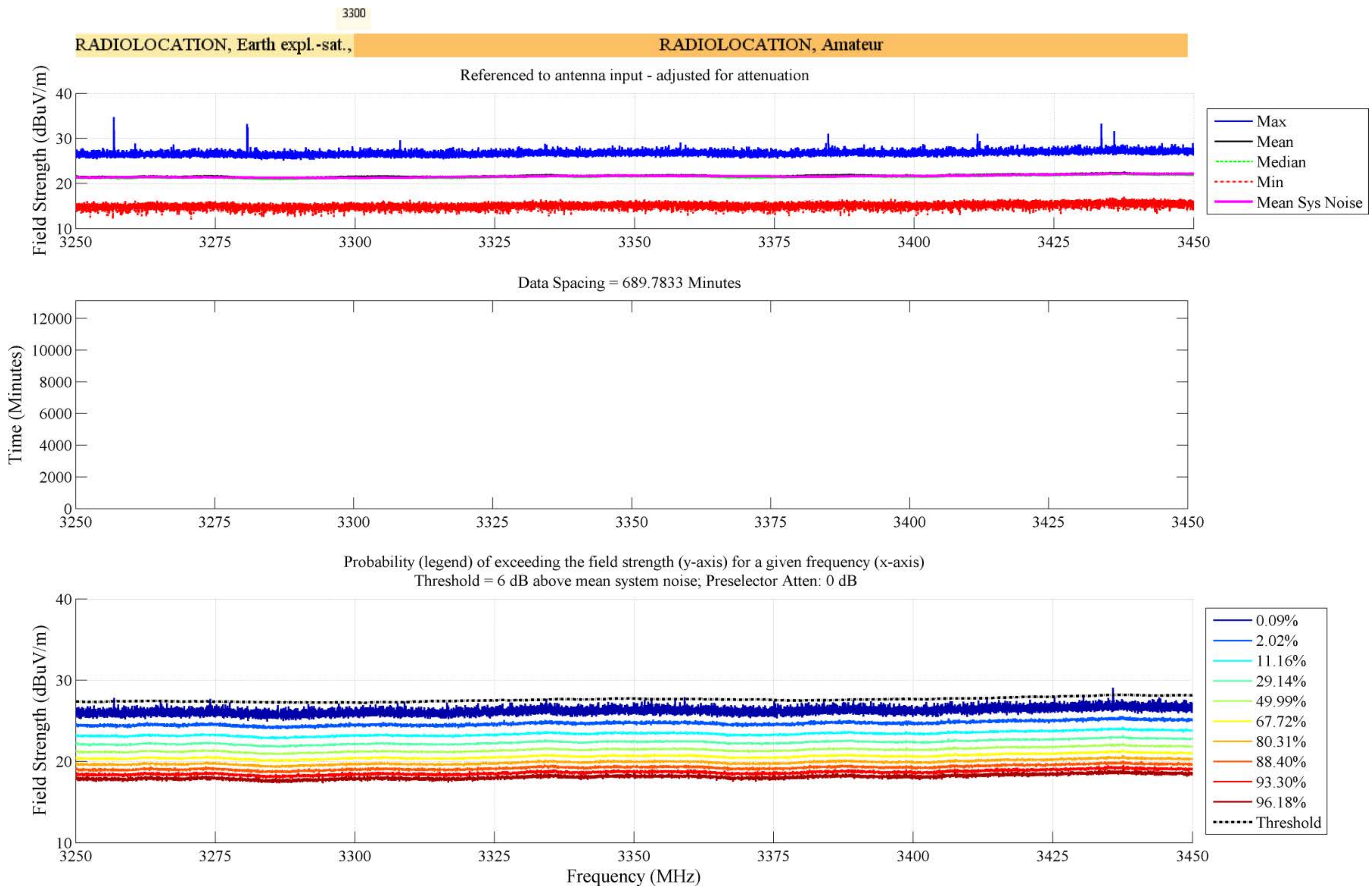

Figure 77. NTIA spectrum survey results from 3250 to 3450 MHz in Chicago, IL, September 2012.

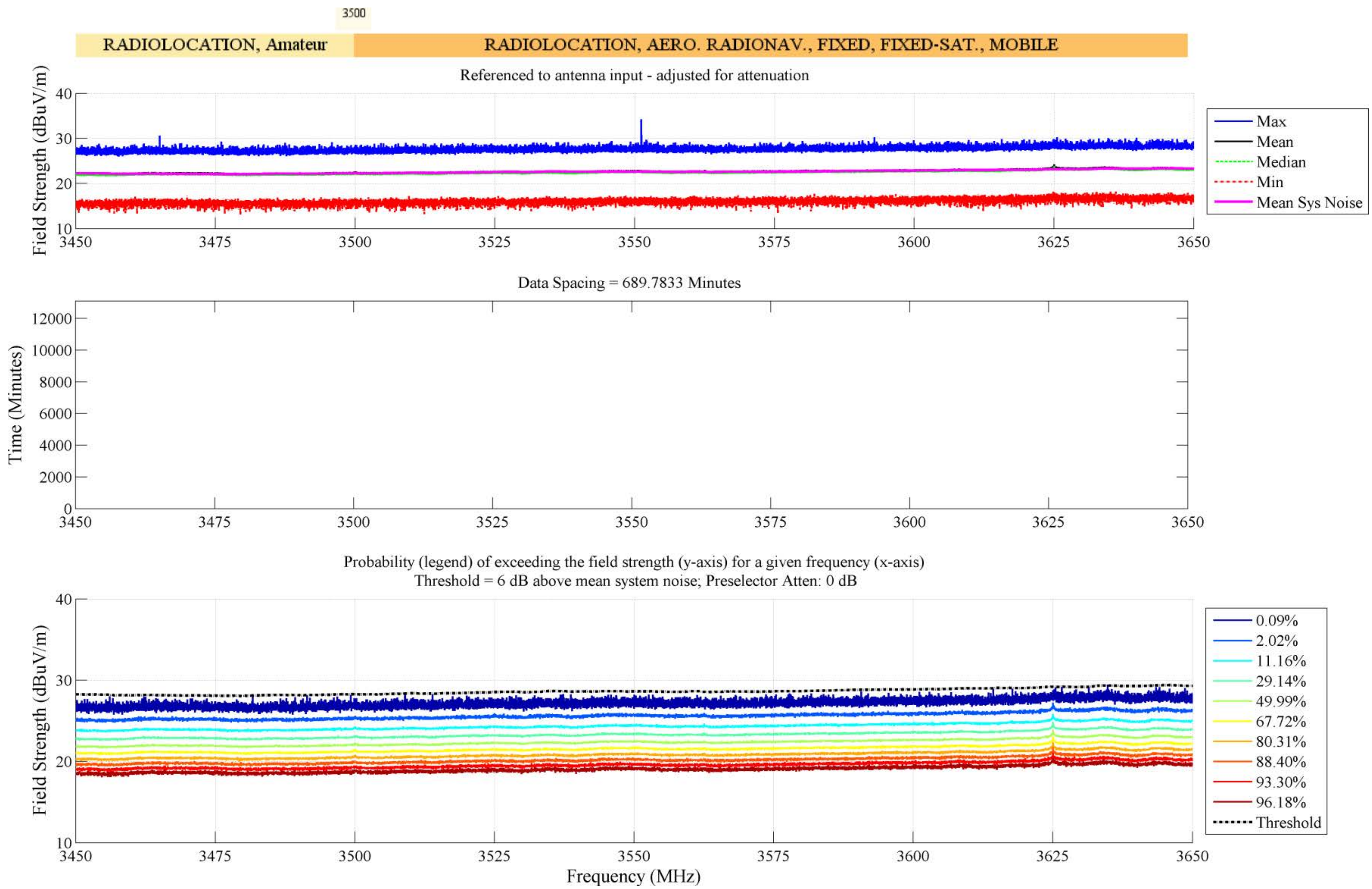

Figure 78. NTIA spectrum survey results from 3450 to 3650 MHz in Chicago, IL, September 2012.

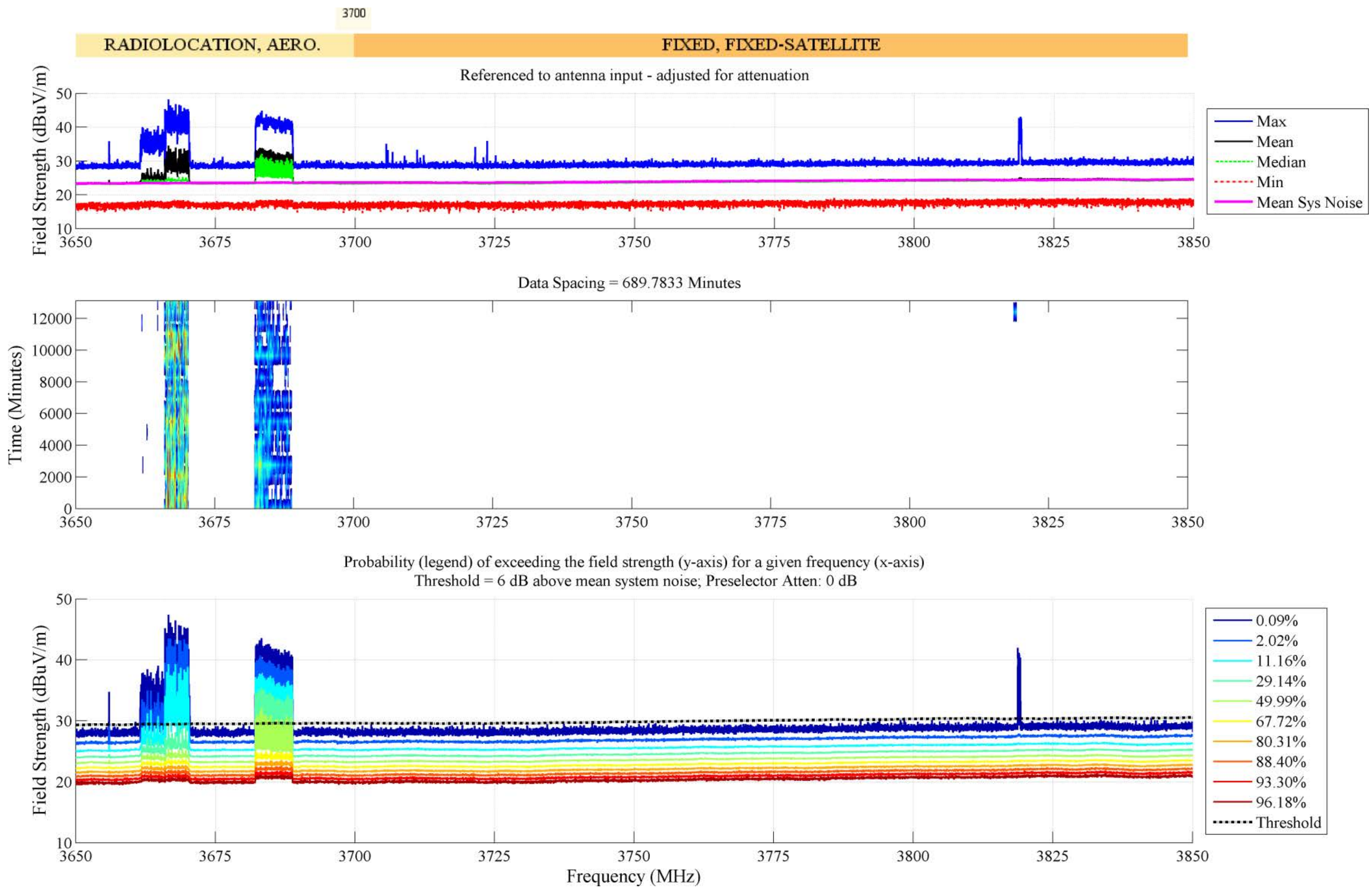

Figure 79. NTIA spectrum survey results from 3650 to 3850 MHz in Chicago, IL, September 2012.

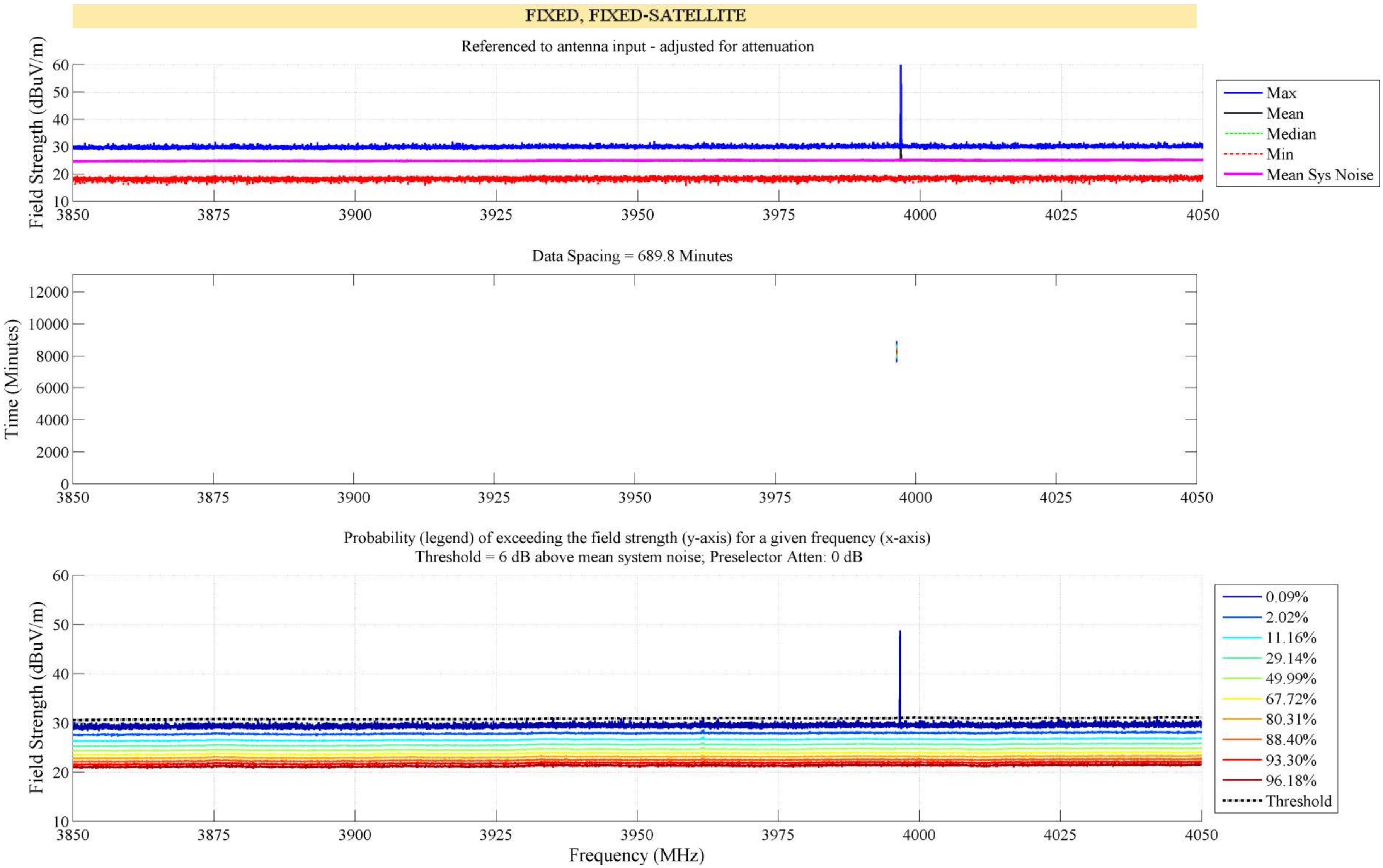

Figure 80. NTIA spectrum survey results from 3850 to 4050 MHz in Chicago, IL, September 2012.

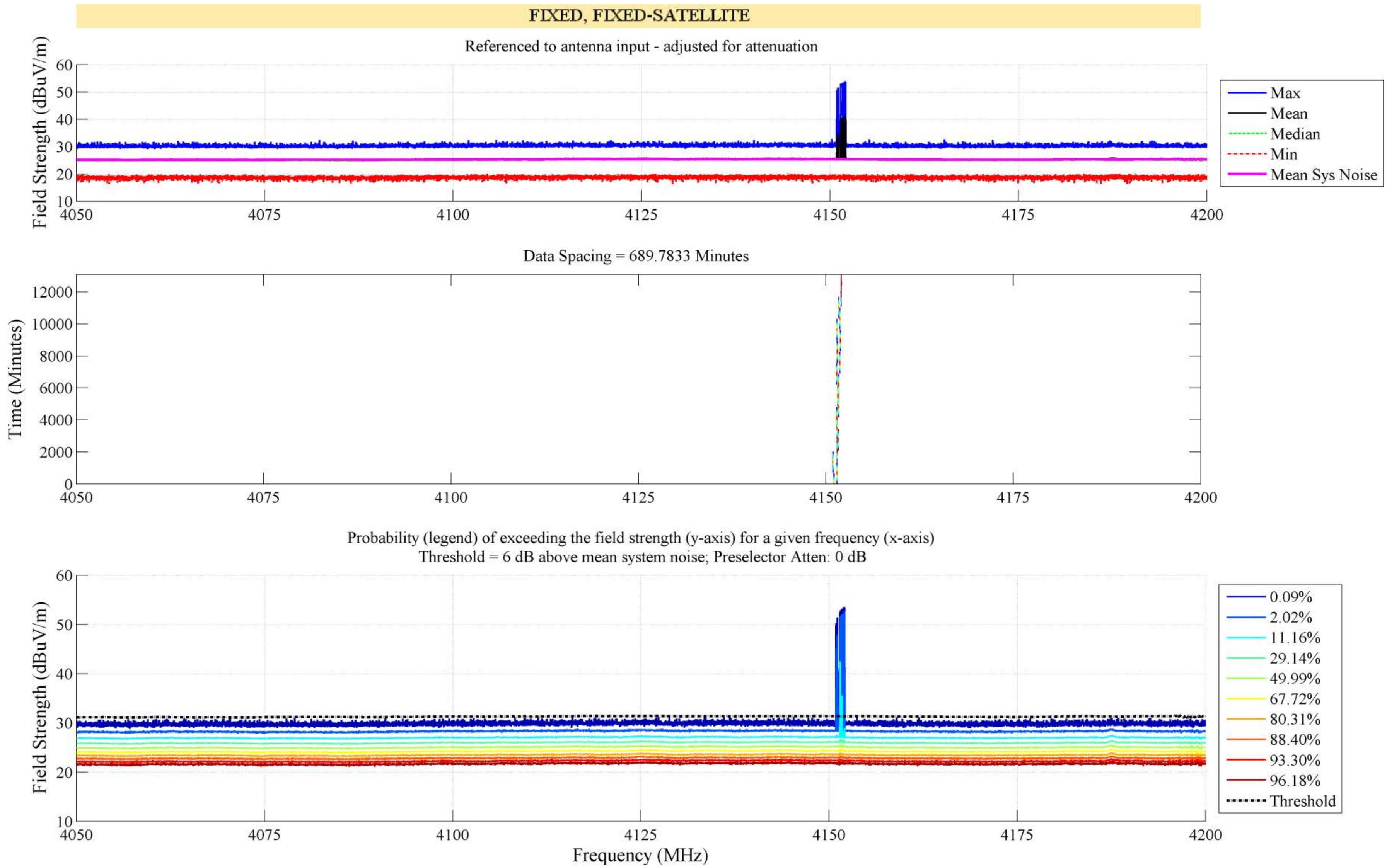

Figure 81. NTIA spectrum survey results from 4050 to 4200 MHz in Chicago, IL, September 2012.

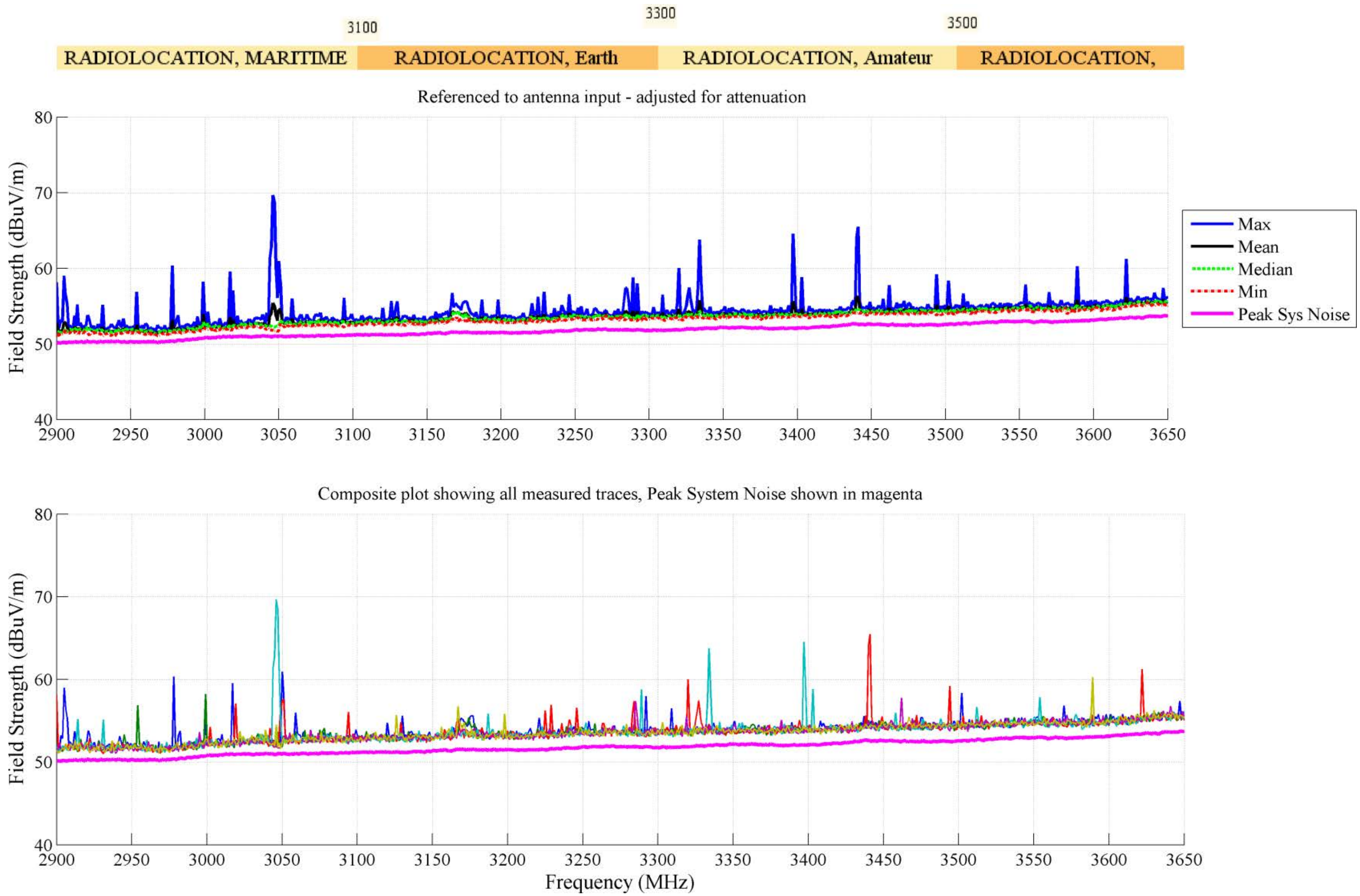

Figure 82. NTIA spectrum survey results from 2900 to 3650 MHz in Chicago, IL, September 2012. This measurement was taken using the stepped-spectrum measurement algorithm.

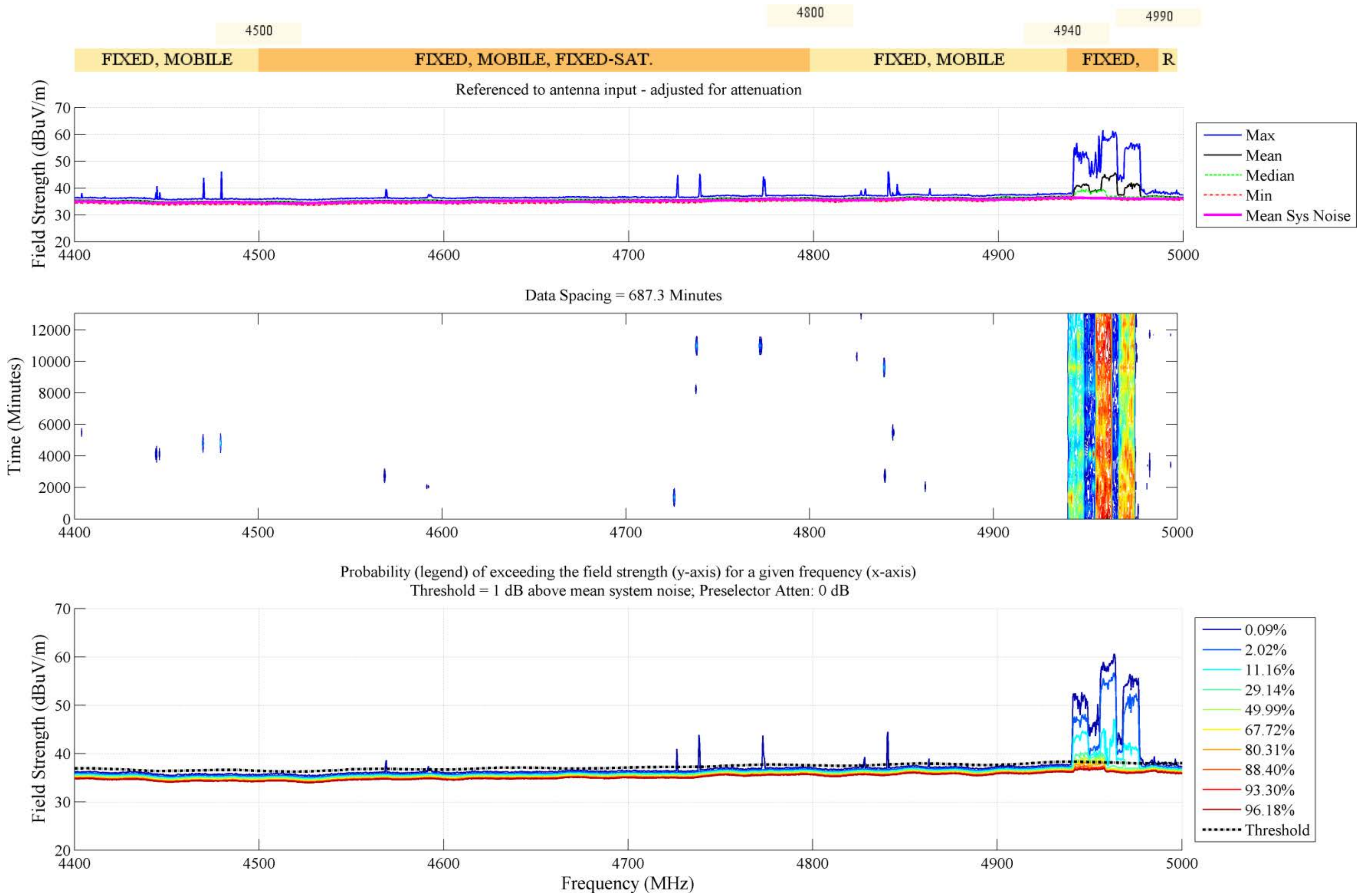

Figure 83. NTIA spectrum survey results from 4400 to 5000 MHz in Chicago, IL, September 2012. This measurement was taken using the swept-spectrum measurement algorithm.

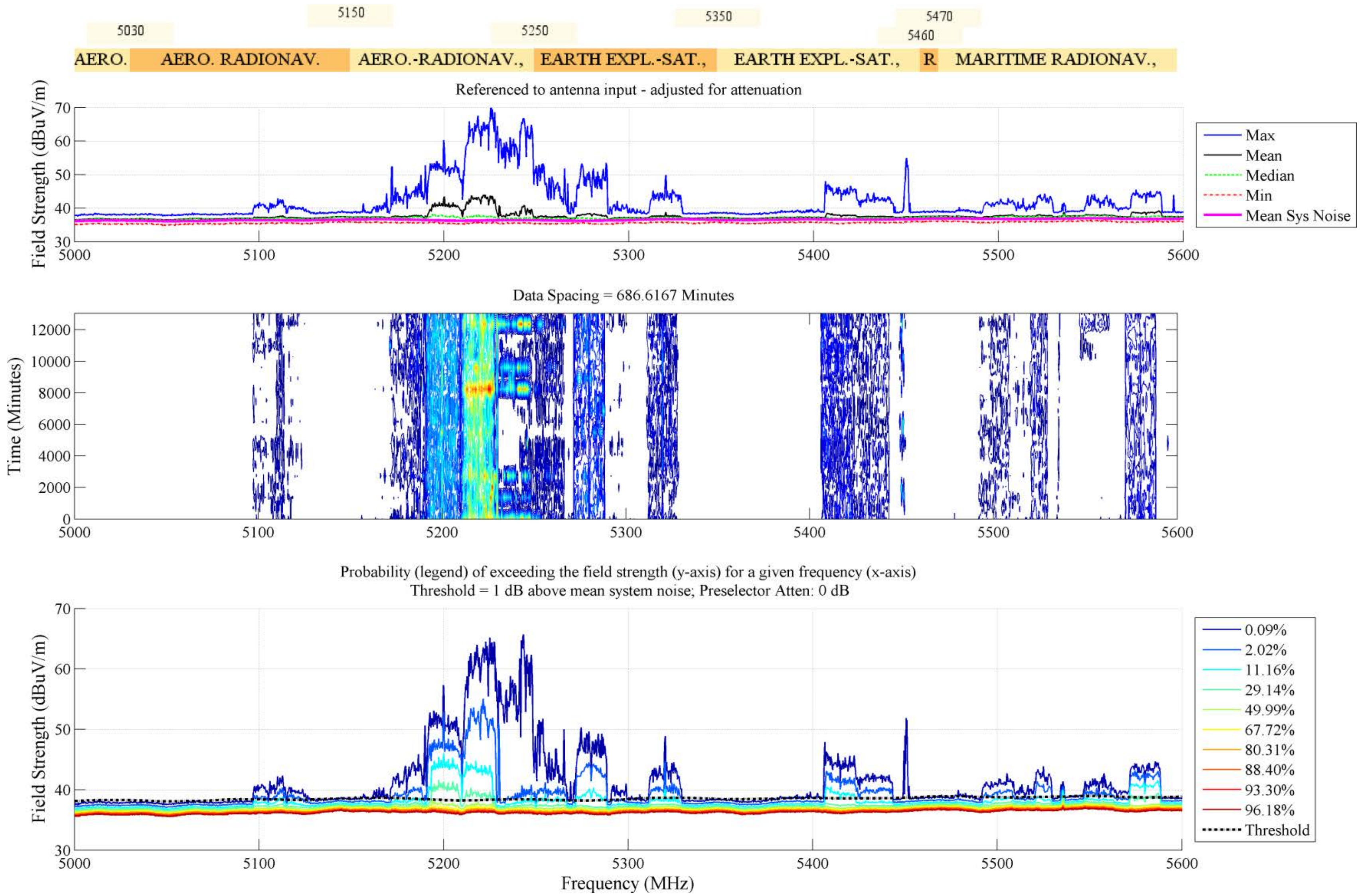

Figure 84. NTIA spectrum survey results from 5000 to 5600 MHz in Chicago, IL, September 2012. This measurement was taken using the swept-spectrum measurement algorithm.

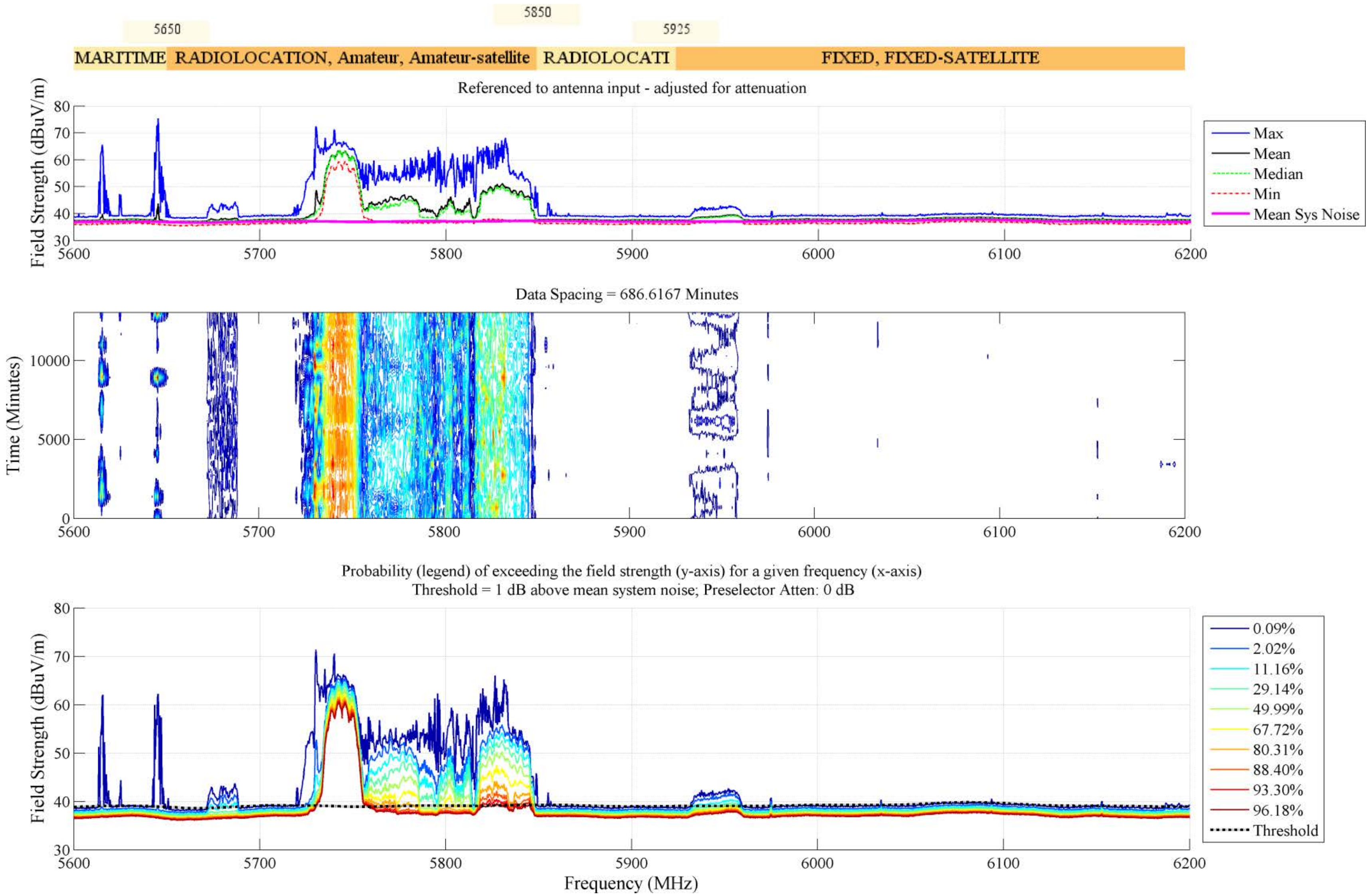

Figure 85. NTIA spectrum survey results from 5600 to 6200 MHz in Chicago, IL, September 2012. This measurement was taken using the swept-spectrum measurement algorithm.

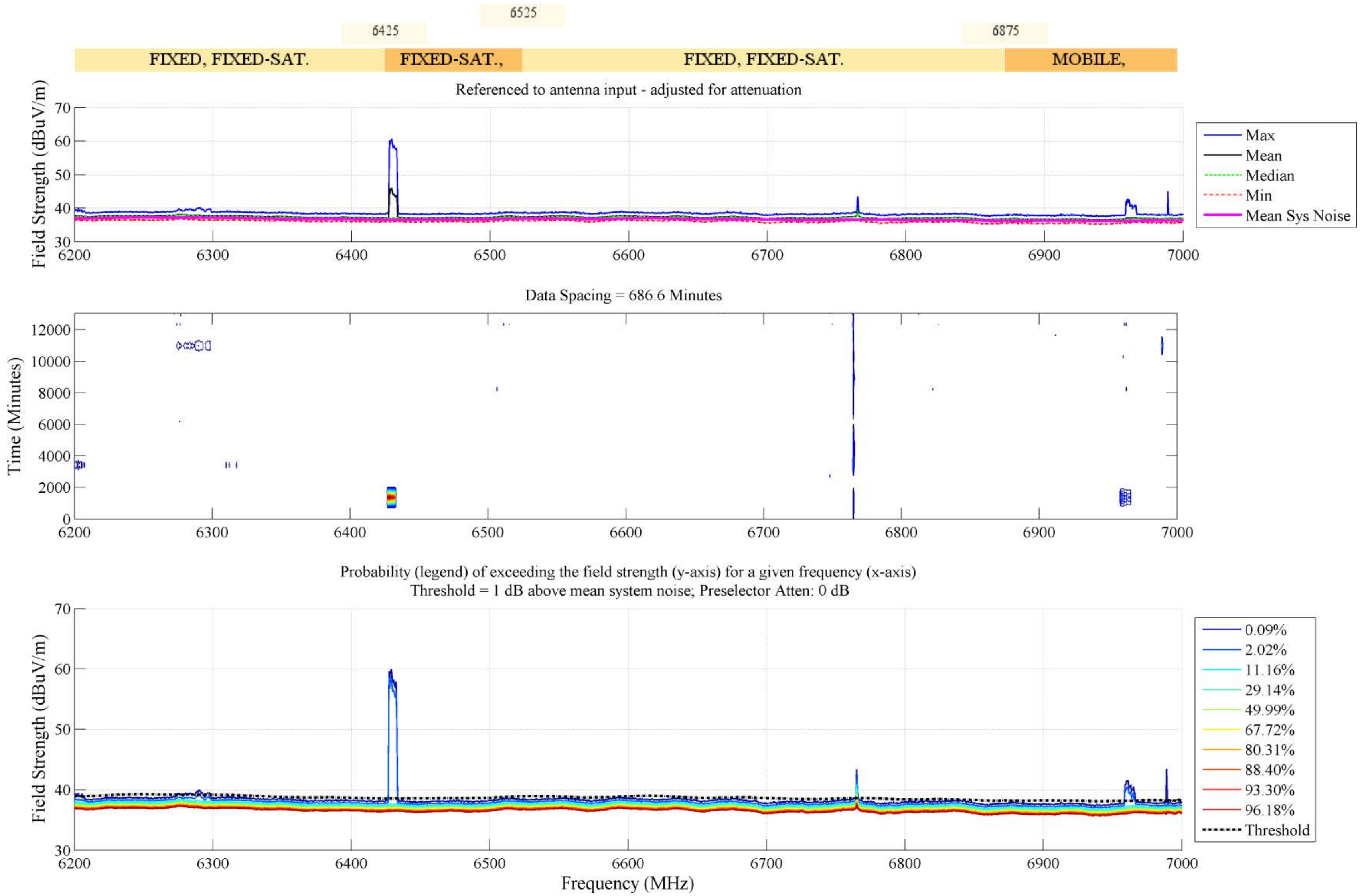

Figure 86. NTIA spectrum survey results from 6200 to 7000 MHz in Chicago, IL, September 2012. This measurement was taken using the swept-spectrum measurement algorithm.

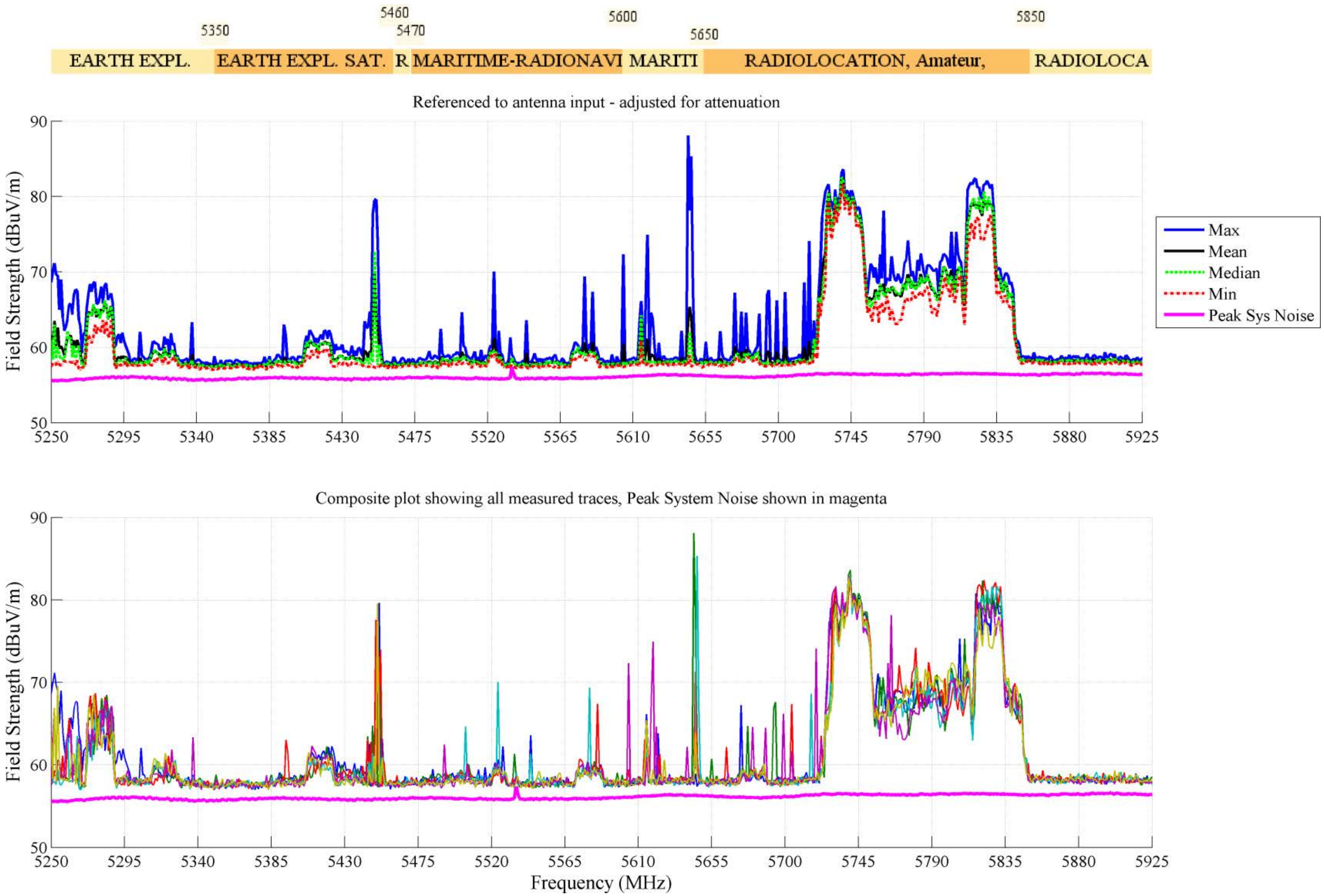

Figure 87. NTIA spectrum survey results from 5250 to 5925 MHz in Chicago, IL, September 2012. This measurement was taken using the stepped-spectrum measurement algorithm.

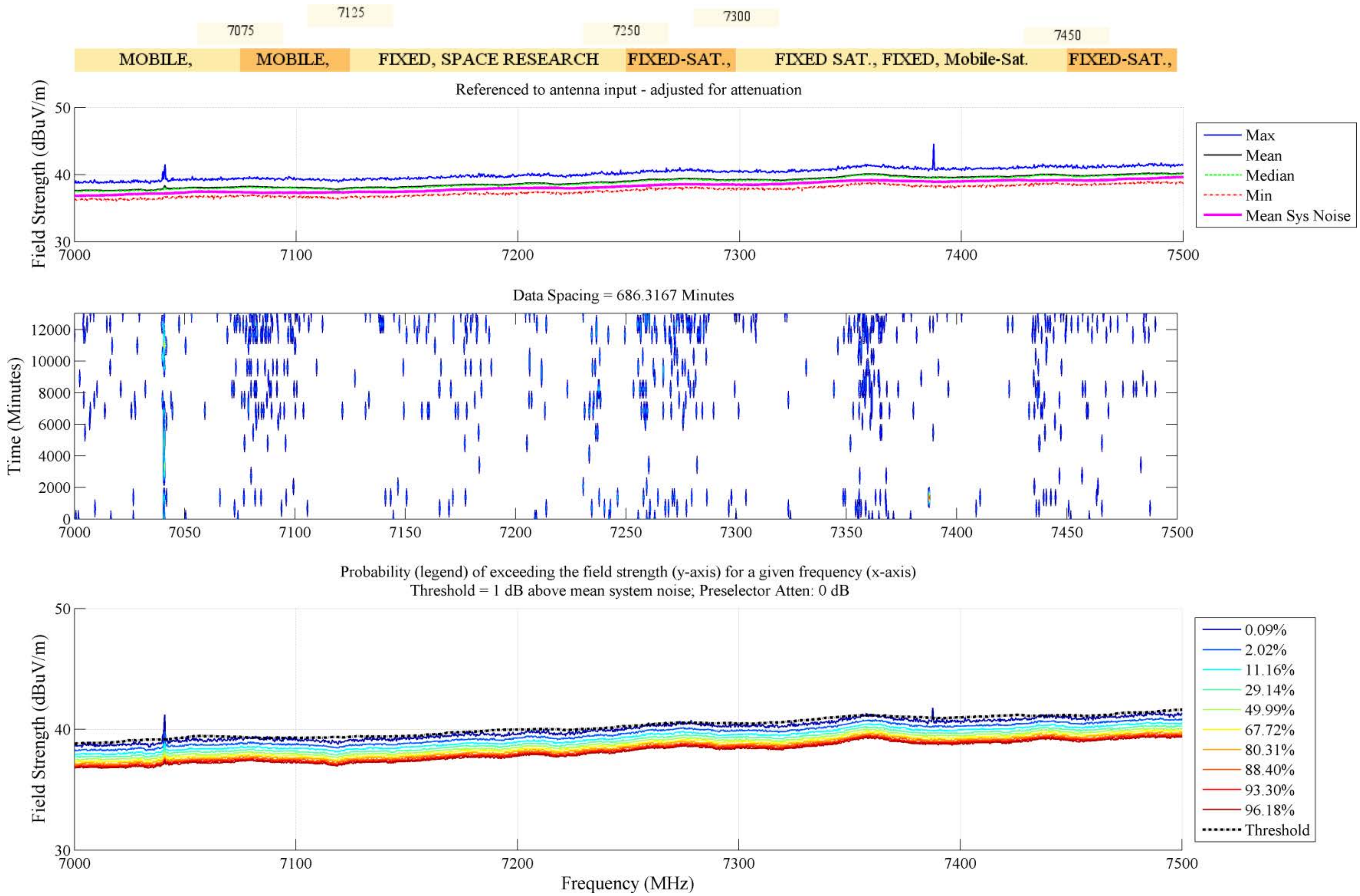

Figure 88. NTIA spectrum survey results from 7000 to 7500 MHz in Chicago, IL, September 2012. This measurement was taken using the swept-spectrum measurement algorithm.

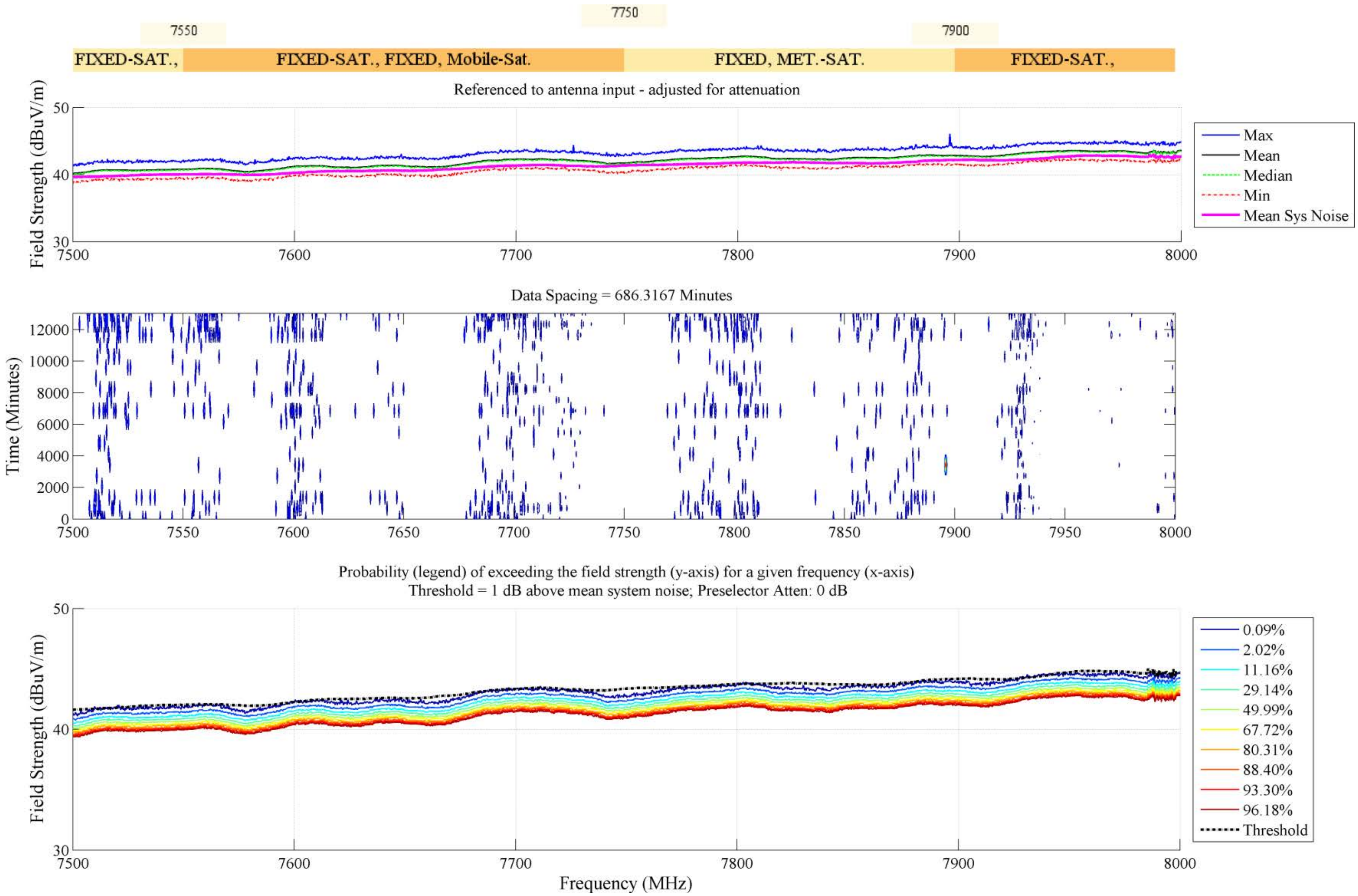

Figure 89. NTIA spectrum survey results from 7500 to 8000 MHz in Chicago, IL, September 2012. This measurement was taken using the swept-spectrum measurement algorithm.

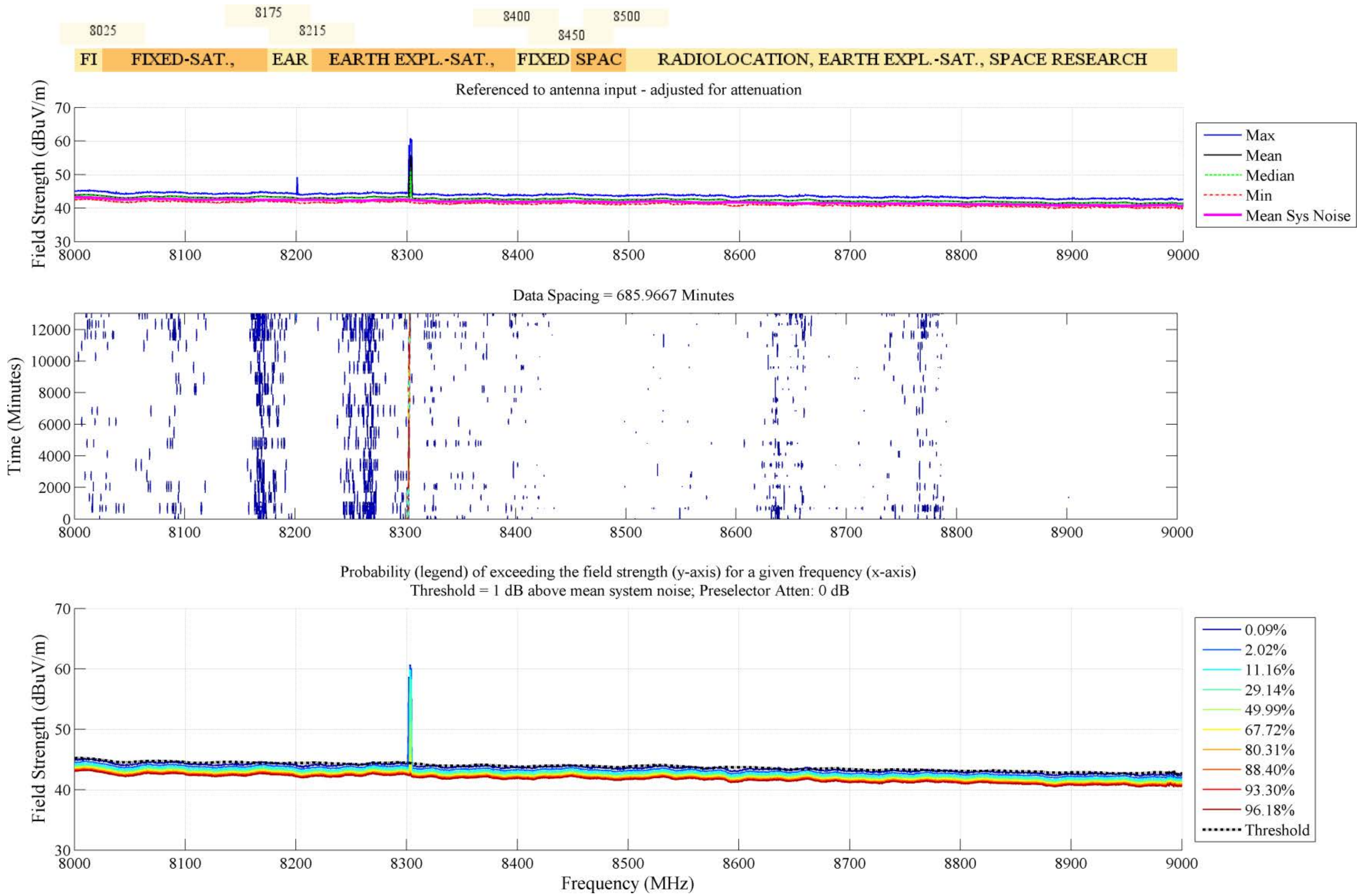

Figure 90. NTIA spectrum survey results from 8000 to 9000 MHz in Chicago, IL, September 2012. This measurement was taken using the swept-spectrum measurement algorithm.

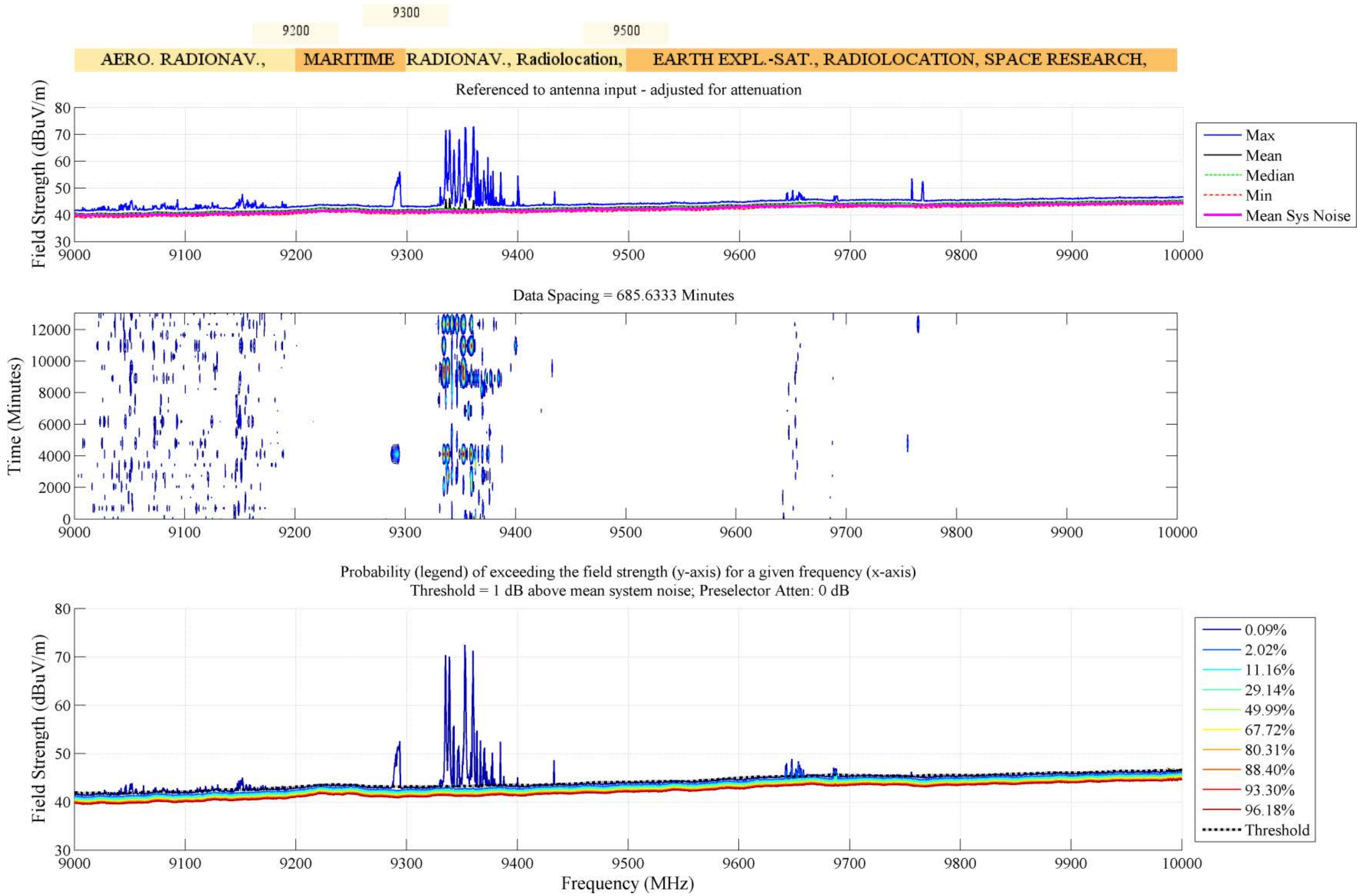

Figure 91. NTIA spectrum survey results from 9000 to 10000 MHz in Chicago, IL, September 2012. This measurement was taken using the swept-spectrum measurement algorithm.

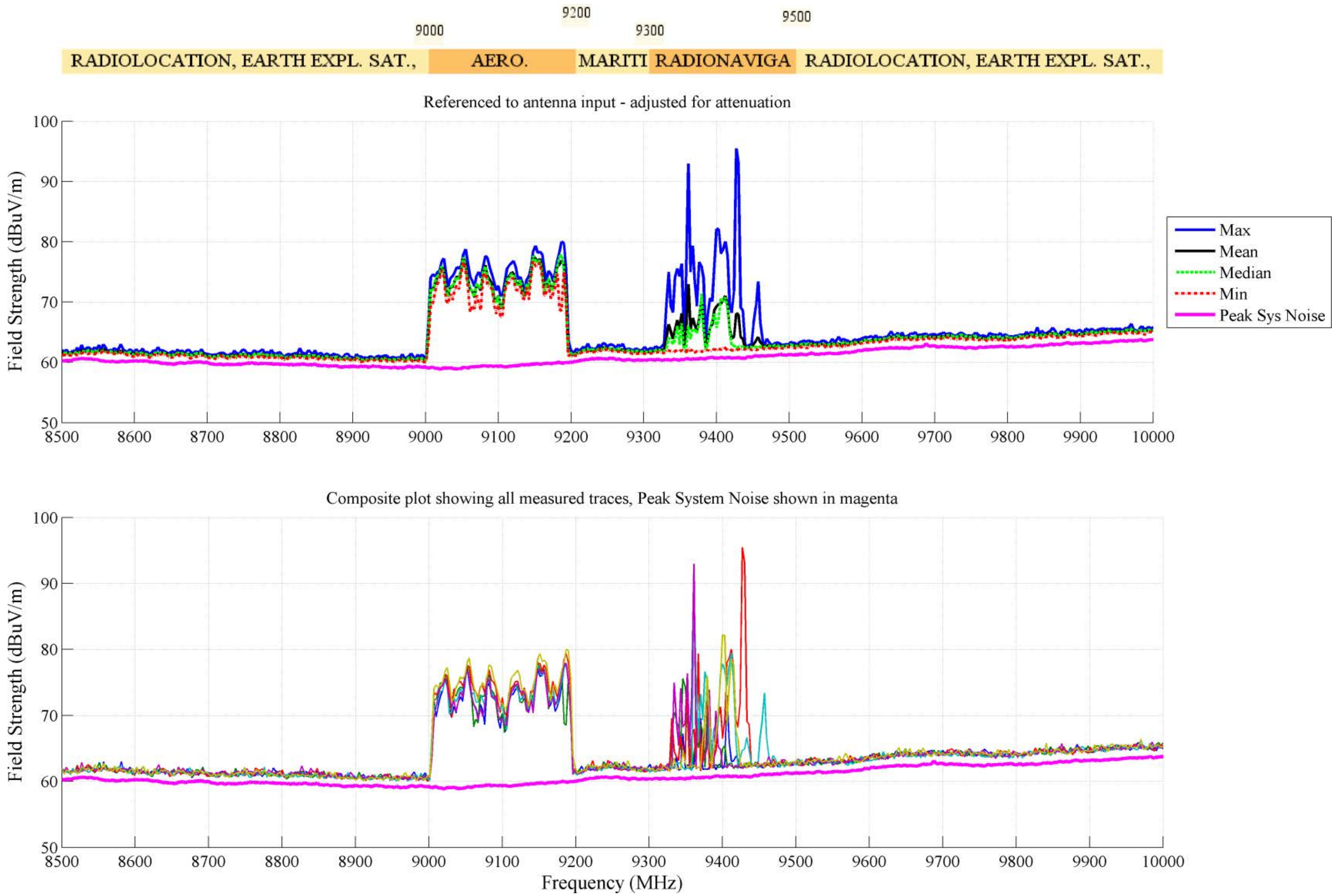

Figure 92. NTIA spectrum survey results from 8500 to 10000 MHz in Chicago, IL, September 2012. This measurement was taken using the stepped-spectrum measurement algorithm.

3.1 Discussion of Measured Data

A discussion of Figures 5, 51, and 59 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], [12], [14] and [15].

Figure 5 shows signals from 112 to 116 MHz. The first thing that catches the eye is the waterfall plot in the middle graph. Typically there are areas of white space in these graphs which indicate areas where signal levels are below the threshold value of 13 dB in this figure. In this graph, we see large areas where signals appear to occupy all frequencies in time. These signals are referred to as impulsive noise and because they occur with very short bursts in the time domain, they appear across all frequencies. We still see signals at approximately 112.5 MHz, 113.0 MHz, 113.9 MHz, 114.0 MHz, and 115.1 MHz. The signal at 115.1 MHz appears above 20 dBμV/m with a probability of 0.09%, whereas, the other signals appear above field strengths of 1–2 dBμV/m with a probability of 96.18%, which means they are on for the entire time the band was measured.

Figure 51 shows signals from 716 to 734 MHz. The abrupt jump at 728 MHz was caused by the addition of a 10 dB attenuator, which is the first attenuator shown in Figure 2. Adding this attenuation avoided system overloads due to the emissions of the LTE signals in the frequency band from 728 MHz to 763 MHz. The signal strength seemed to vary throughout the survey so the attenuation was added as needed. No prominent signals are seen in the frequency band from 716 to 728 MHz.

Measurements from 935 to 962 MHz show some interesting effects (Figure 59). There is an underlying signal from 0 to approximately 2000 minutes which then appears to turn off for the rest of the survey. That the signal appears to turn off is actually due to the addition of attenuation after the 2000 second time frame. The additional attenuation was added to keep the system from overloading; however, adding attenuation decreases the system sensitivity. After the addition of attenuation, these signal levels are below the 6 dB threshold and do not appear on the graph. The 1 MHz wide signal around 948 MHz shows various levels of activity. At this frequency, for probabilities between 0.09% and 49.99%, the signal levels vary from approximately 56 to 63 dBμV/m. The signal level at 948 MHz is around 30 dBμV/m with a probability of 67.72%, the signal level exceeds 20 dBμV/m with a probability of 80.31%, and the signal exceeds approximately 15 dBμV/m with a probability of 96.18%. The signals above 954.0 MHz are intermittent.

Table 4. Notes on Figures 4–92.

Figure(s)	Frequency Range (MHz)	Notes
4-6	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. These signals can raise the noise floor in the 108–112 MHz frequency band. To suppress FM signal leakage above 108 MHz, we inserted 20 dB of preselector attenuation from 108–112 MHz and 10 dB of preselector attenuation from 112–116 MHz into the system and a high-pass filter, which may affect the ability of our system to detect the low-level aeronautical radionavigation signals.
6-9	117.975–136.0	The aeronautical mobile signals in this band originate from air traffic control (ATC), private aircraft, and search and rescue. The FAA uses this band for ATC via the Automated Weather Observation System (AWOS) and the Automated Terminal Information System (ATIS). These signals are characterized by their small bandwidth. There are many signals in the band from 124.0 to136.0 MHz. Many of these signals only exceed their field strength levels for less than 2.02% of the time. We had to increase the threshold level in these bands due to external noise sources.
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) up to 137.0 MHz. 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). There are only a few strong signals in these two bands.
10, 11	138.0–144.0	This band is generally used for non-tactical, trunked military land mobile communications and civil air patrol. There is a broadband signal from 139.5 to 140.5 MHz that appears to change frequency. There is also a lot of impulsive noise in this band as well as signals that were on during the entire spectrum survey.
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. The signals in this band are narrowband, some are on intermittently and others are on continuously. There is also a lot of impulsive noise which shows up as horizontal lines that cross all frequencies during certain time frames.
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 are found between 156.2475–157.1875 MHz and 161.575–162.0125 MHz. The frequencies from 150.8 to 162.0 were heavily used during this spectrum survey.
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. There is an unusual signal at approximately 165.3 MHz. This band does not appear to be heavily used during this survey.

Figure(s)	Frequency Range (MHz)	Notes
17-20	174.0–216.0	This part of the spectrum is used for broadcasting television. Channels 7, 8, 10, 11, and 12 are occupied with Advanced Television Systems Committee (ATSC) transmissions. There are a few 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.
21	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 a wider-band signal at approximately 216.2 MHz and a signal that varies in frequency at approximately 217.1 MHz
21, 22	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 (1.25 m band) radio. We see very short-duration signals from approximately 220.2 MHz to 220.95 MHz and again from 224.1 MHz to 225.0 MHz. .
23-29	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. There is a strong environmental signal that results in periodic oscillations of the spectrum from approximately 281 MHz to 313 MHz.
29	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 do not see a lot of spectrum use in this band.
29-32	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. There are areas of wideband activity from approximately 330 MHz to 332.5 MHz and again from approximately 358 MHz to 363.5 MHz. There is also a wideband signal that appears from 350 MHz to 354 MHz but only during the last 15 hours of the survey. Otherwise, these are not heavily used bands.

Figure(s)	Frequency Range (MHz)	Notes
32	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 see an intermittent signal in this band in Chicago. The allocation for 400.05–400.15 MHz is the “STANDARD FREQUENCY AND TIME SIGNAL-SATELLITE” at 400.1 MHz ± 25 kHz. There was one signal from 400.05 to 400.15 MHz. Meteorological aids occupy the band 400.15–406.0 MHz and include National Oceanic and Atmospheric Administration (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. There were only a few signals on very intermittently during the survey.
33-35	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. There was a strong intermittent signal at approximately 406.1 MHz. 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 are a few strong continuous signals in this band and a number of intermittent signals.
36-38	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 38) to detect radar signals and a swept-spectrum measurement algorithm (Figures 36 and 37) to detect all other signals. There is heavy, intermittent spectrum usage from 440 MHz to 450 MHz.
39, 40	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 plots.

Figure(s)	Frequency Range (MHz)	Notes
40-42	470.0–512.0	These bands are used by fixed, land-mobile and broadcasting services. Uses in this band include public mobile, broadcast radio (Channels 14–20), 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. ATSC broadcast signals occupy channels 17, 18, and 19.
42-53	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 23, 24, 34 and 41 are still in the old National Television Systems Committee (NTSC) transmission format. We received signals from ATSC transmitters in channels 21, 25, 27–33, 35, 36, 38–40, 42–45, 47, 48, 50 and 51. 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, which 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 740.0 to 745.0 MHz and from 746.0 to 756.0 MHz we see digitally-modulated signals which appear to be related to Long Term Evolution (LTE).
53-56	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. Figures 54 and 55 show intermittent usage from 806 to 824 MHz and heavy usage from 824 to 835 MHz and from 851 to 894 MHz.
57, 58	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, and NOAA wind profiler systems; this is also one of the ISM bands. This frequency range was measured using a stepped-spectrum measurement algorithm (Figure 58) to detect radar signals and a swept-spectrum measurement algorithm (Figure 57) to detect all other signals. The waterfall plot shows no distinct signals in this band during this spectrum survey; however, the mean spectrum is raised above the system noise floor which indicates some sort of constant source.
57, 59	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. The frequencies from 928.0 to 954.0 MHz show heavy usage during our survey.

Figure(s)	Frequency Range (MHz)	Notes
59-62	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 frequencies from 960.0 to approximately 1020.0 MHz and from 1150.0 MHz to 1215.0 MHz are not heavily used. The ATCRBS signals are seen at 1030 and 1090 MHz.
62-64	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 64) to detect radar signals and a swept-spectrum measurement algorithm (Figures 62 and 63) to detect all other signals. We see radar emissions between 1240 and 1390 MHz in Figure 64. Radar emissions at approximately 1260 MHz, 1315 MHz, and 1350 MHz shown in Figures 62 and 63 in the swept-spectrum measurements were also detected in the stepped-spectrum measurements shown in Figure 64. Notice that the peak power shown in the swept-spectrum measurements is around 50 dBμV/m for the radar emissions at 1260 MHz and 1315 MHz, whereas in the stepped-spectrum measurement the actual peak powers are 110 dBμV/m for the radar at 1260 MHz and 100 dBμV/m for the radar at 1315 MHz.
63, 65	1400.0–1427.0 1427.0–1535.0	The allocation from 1400.0 to 1427.0 is for earth exploration satellites, radio astronomy, and space research applications. This band is a passive band which means that it is a receive-only band. We did not see activity in this band during the spectrum survey. 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. We saw little activity in these bands during the survey.

Figure(s)	Frequency Range (MHz)	Notes
65, 66	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 TIROS-N. The heaviest activity occurred in the frequency range from 1610 to 1626.5 MHz.
66, 67	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) and Space-Ground Link System (SGLS), telemetry, and telecommand. We saw three wideband signals at approximately 1735.0 MHz, 1740.0 MHz, and 1745.0 MHz.
67-69	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 bands from 1850 to 1910 MHz and 1930 to 1990 MHz, which show heavy usage.
69, 70	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 Deep Space Network (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. There appear to be digital signal transmissions from 2075 MHz to 2155 MHz. All other band usage is minimal. The addition of 20 dB of preselector attenuation is shown from 2100 MHz to 2200 MHz.
71, 72	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 digital signals from 2325.0 to 2340.0 MHz and various signal types from 2400.0 to 2483.5 MHz which include microwave oven emissions.

Figure(s)	Frequency Range (MHz)	Notes
72, 73	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. For the digital signals seen in this band above 2500 MHz, all probability levels show activity for the entire survey.
74	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. These signals were measured using the stepped-spectrum algorithm developed to detect radars. There are several distinct frequencies that show activity in this band in the Chicago area. They are at 2715 MHz, 2745 MHz, 2750MHz, 2770 MHz, 2780 MHz, 2795 MHz, 2820 MHz, 2840 MHz, 2855 MHz, and 2870 MHz.
75-79, 82	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 75–79) were made from 2900.0 to 3700.0 MHz and stepped-spectrum measurements (Figure 82) were made from 2900.0 to 3650.0 MHz (a radar band). The swept measurements show some digital signals from 3660 MHz to 3690 MHz in Figure 79. In Figures 75 and 82, we can compare the results of a swept- versus a stepped-spectrum measurement which shows the same signal at 3050 MHz. The signal has a field strength of approximately 37 dBμV/m in Figure 75 and a value of approximately 62 dBμV/m in Figure 82. Stepped-spectrum measurements record the peak value of the signal and typically measure signals with a longer dwell time. There is also a low-level signal at 3175 MHz in Figure 76 which is the same small signal seen in the stepped-spectrum measurement (Figure 82).
79-81	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. There are three signals seen at 3820 MHz, 3995 MHz, and 4155 MHz. Only the signal at 4155 MHz was on for the entire survey, the other signals were on only once during the survey.
--	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 did not measure this band during the Chicago survey due to time constraints.

Figure(s)	Frequency Range (MHz)	Notes
83	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. The only signals on continuously in this band were at approximately 4950 MHz, 4970 MHz, and 4980 MHz.
84	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. Signals appeared between 5090–5130 MHz and again from 5170 to 5250 MHz.
84, 85, 87	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 87. The signals from 5250 to 5320 MHz, from 5400 to 5450 MHz, from 5495 to 5600 MHz, 5620 MHz, 5650 MHz, 5675 MHz, and from 5725 to 5850 MHz shown in the swept-spectrum measurements of Figures 84 and 85 show up in the stepped-spectrum measurements of Figure 87 as well.
84, 85, 87	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). There does not appear to be much activity in this frequency band during the spectrum survey.
88-90	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. There was only one prominent signal in this frequency range during the spectrum survey at 8300 MHz. It was active during the entire spectrum survey.

Figure(s)	Frequency Range (MHz)	Notes
90-92	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 90 and 91), and stepped-spectrum methods (Figure 92), The signal from 9350 to 9390 MHz was measured using both swept- and stepped-spectrum methods. The signal from 9000 to 9200 MHz shows up very prominently in the stepped spectrum measurement (Figure 92), and shows up only in the waterfall plot (Figure 91) for the swept-spectrum measurement algorithm.

4 ACKNOWLEDGEMENTS

The author wishes to thank Dennis Roberson, Philip Felber, Ken Zdunek, Roger Peterson, Ed Porrett, and Steve Sundberg from Roberson and Associates for all of their assistance and the invitation to measure on IIT's campus. The author also wishes to thank Heather Ottke who was an essential person during the spectrum survey and suggested many quality improvements to the prior reports. Frank Sanders is acknowledged for many conversations regarding spectrum assignments and allocations. His prior reports on spectrum surveys served as invaluable references for this work. Thanks also to Eric Nelson, Division Chief, for his leadership and guidance during the process of writing this report.

5 REFERENCES

[1] U.S. Department of Commerce, National Telecommunications and Information Administration, (NTIA), Manual of Regulations and Procedures for Federal Radio Frequency Management, Chapter 2, Washington, D.C., revised May 2011. http://www.ntia.doc.gov/page/2011/manual-regulations-and-procedures-federal-radio-frequency-management-redbook

[2] United States Department of Commerce, Department Organization Order 25-7, http://www.osec.doc.gov/opog/dmp/doos/doo25_7.html

[3] Chriss Hammerschmidt, Heather E. Ottke, J. Randy Hoffman, “Broadband Spectrum Survey in the Denver Area,” NTIA Report TR-13-496, August, 2013. http://www.its.bldrdoc.gov/publications/2735.aspx

[4] Chriss Hammerschmidt, “Broadband Spectrum Survey in the San Diego Area,” NTIA Report TR-14-498, November, 2013. http://www.its.bldrdoc.gov/publications/2741.aspx

[5] Frank Sanders, Vincent Lawrence, and Robert Hinkle, “Broadband Spectrum Survey at Denver, Colorado,” NTIA Report TR-95-321, September 1995, http://www.its.bldrdoc.gov/publications/2353.aspx

[6] F.H. Sanders, B.J. Ramsey, and V.S. Lawrence, “Broadband Spectrum Survey at San Diego, California,” NTIA Report TR-97-334, December 1996. http://www.its.bldrdoc.gov/publications/2366.aspx

[7] M.A. McHenry, D. McCloskey, D. Roberson, J.T. MacDonald, “Spectrum Occupancy Measurements Chicago, Illinois,” Shared Spectrum Co., December 20, 2005, accessed 12/10/2013, http://www.sharedspectrum.com/wp-content/uploads/NSF_Chicago_2005-11_measurements_v12.pdf.

[8] F.H. Sanders, B.J. Ramsey, and V.S. Lawrence, “Broadband Spectrum Survey at Los Angeles, California,” NTIA Report TR-97-336, May 1997, http://www.its.bldrdoc.gov/publications/2368.aspx

[9] F.H. Sanders, B.J. Ramsey, and V.S. Lawrence, “Broadband Spectrum Survey at San Francisco, California,” NTIA Report TR-99-367, July 1999. http://www.its.bldrdoc.gov/publications/2398.aspx

[10] M. J. Chrzastowski, “Chicagoland, Geology and the Making of a Metropolis,” Field Excursion for the 2005 Annual Meeting of the Association of American State Geologists, June 2005.

[11] F.H. Sanders, G. R. Hand, and V. S. Lawrence, “Land mobile radio channel usage measurements at the 1996 Summer Olympic Games,” NTIA Report TR-98-357, Sep. 1998. http://www.its.bldrdoc.gov/publications/2388.aspx

[12] NTIA, "United States Frequency Allocation Chart," http://ntia.doc.gov/page/2011/united-states-frequency-allocation-chart.

[13] J.R. Hoffman, R.J. Matheson, and R.A. Dalke, "Measurements to characterize land mobile channel occupancy for Federal bands 162-174 and 406-420 MHz in the Washington, D.C., area," NTIA Report TR-07-448, July 2007, http://www.its.bldrdoc.gov/publications/2485.aspx.

[14] 47 C.F.R. § 2.106 Table of Frequency Allocations (2012). http://www.ecfr.gov/

[15] NTIA, "Federal Spectrum Use Summary," June 2010, http://www.ntia.doc.gov/legacy/osmhome/osmhome.html.

[16] Sanders, F.H., R.L. Hinkle, and B.J. Ramsey, "Measurement procedures for the radar spectrum engineering criteria (RSEC)," NTIA Report TR-05-420, U.S. Department of Commerce, Mar. 2005, http://www.its.bldrdoc.gov/publications/2450.aspx.

[17] NTIA, "U.S. National Spectrum Requirements: Projections and Trends," NTIA Special Publication 94-31, March 1995. http://www.its.bldrdoc.gov/publications/2672.aspx

[18] Public Safety Wireless Advisory Committee, "Final report of the public safety wireless advisory committee," accessed 10/3/2011, http://ntiacsd.ntia.doc.gov/pubsafe/publications/PSWAC_AL.PDF .

[19] 47 C.F.R. §90 (2010), Private Land Mobile Radio Services. http://www.ecfr.gov/

[20] Achatz, R. J., Dalke, R. A., "Man-Made Noise Power Measurements at VHF and UHF Frequencies," NTIA Report 02-390, U.S. Department of Commerce, Dec. 2001. http://www.its.bldrdoc.gov/publications/2421.aspx

[21] Niedzielski, R.A., "Environmental Impulse Noise Study," NPC Library,1991., http://www.nonoise.org/library/impulse/impulse

[22] R.A. Dalke, "Radio Noise," in Wiley Encyclopedia of Electrical and Electronics Engineering, J. Webster, Ed., New York: Wiley, 2005, pp. 128-140.

APPENDIX A: FFT MEASUREMENT ALGORITHM

The fast Fourier transform (FFT) measurement algorithm is used to measure the short, impulsive-type signals below 500 MHz found in the mobile service frequency bands. A mobile service is defined as radio communication between mobile and land stations, or between mobile stations. This includes the land, maritime, and aeronautical mobile services, as well as common carriers such as cellular telephone and radio paging [17]. Frequencies below 500 MHz are occupied mostly by land, maritime, and aeronautical mobile services. Land mobile services are usually referred to as land mobile radio (LMR) services.

A.1 Mobile Service Characteristics

Mobile channels are usually occupied by signals from emergency first responder organizations, public works departments, or companies having large fleets of vehicles and field staff. The Department of Defense (DoD) also uses these types of communication systems for both government and military use. Transmitters can be found on fixed towers, mobile platforms, such as cars, and aircraft, and pedestrians in both urban and rural environments. Receivers are fixed or mobile. LMR signals are found in both urban and rural areas.

Mobile bands are channelized according to very specific rules and typically vary from one geographical location to the next. Mobile channel bandwidths can be 6.25 kilohertz (kHz), 12.5 kHz, 15 kHz, 20 kHz, 25 kHz, or 30 kHz depending on the frequency band [13]. Typical mobile messages are five seconds in duration, but no shorter than one second, and transmitted at high power (typically 5–25 W) [11], [18], [19]. Mobile radio signal power received at the measurement system can vary with time and span a range as great as 100 dB in received power. The weakest signals propagate from distant transmissions and the stronger signals propagate from nearby base stations and local mobile and hand-held units near the measurement system. Not only can a single frequency assignment vary greatly in power over time, but power can vary greatly between adjacent frequencies. Due to the broad range of received signal powers, the receiver must have a wide instantaneous dynamic range (i.e., be able to resolve the individual signals without varying the sensitivity of the measurement system across the band of acquisition).

Mobile signal populations are expected to be quite variable and random over short time periods, as specific radio devices are intermittently used. These signals may also exhibit long term daily, weekly, or event-related usage cycles. Although these channels may be used intermittently, they may require immediate channel access in an emergency and the channel may be fully occupied for the duration of this event.

A.2 Measurement Algorithm

The FFT measurement algorithm was developed to address shortcomings in conventional swept measurement methods when used in this environment. There were four distinct improvement goals: (1) a flattop bandpass shape that sharply reduces signals from adjacent LMR channels, (2) removal of impulsive noise, (3) faster measurement acquisitions, and (3) suppression of system noise to allow lower-amplitude occupancy thresholds. The first three improvements are achieved using the time-domain acquisition mode in a spectrum analyzer and adjusting certain parameters while in this mode. The fourth improvement is attained with a post-processing algorithm developed within ITS.

The first improvement uses the flat-top window which is a default setting in the spectrum analyzer. This particular window is applied to the time-domain trace to reduce side-band noise and improve the amplitude accuracy. Figure A-1 shows the FFT of a continuous wave (CW) signal measured using the flat-top window with a 6.25 kHz RBW. The spectrum analyzer's flat-top window provides 80 dB of sideband suppression out to 8 kHz on each side of the center frequency. This makes it possible to resolve individual narrowband signals with as much as 80 dB difference in power and spaced within a standard 12.5 kHz channel spacing.

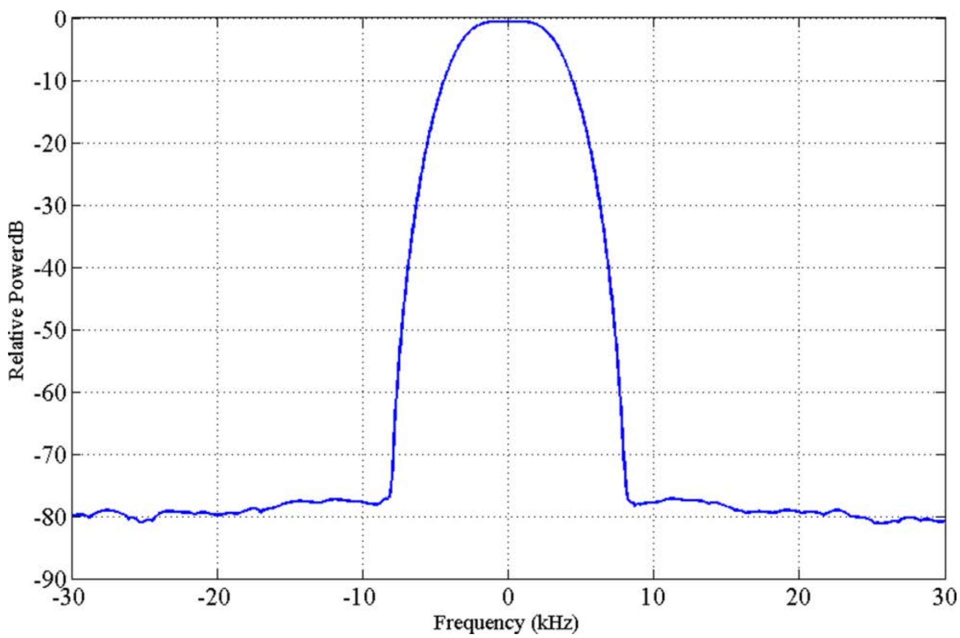

Figure A-1. FFT of CW signal measured using the flat-top window with a 6.25 kHz RBW.

The FFT measurement algorithm allows for faster acquisitions because all frequency components within a span are measured at the same time. This acquisition or capture time depends on the window type and resolution bandwidth settings in the spectrum analyzer. For an RBW of 6.25 kHz, the capture time is 600 µs and for an RBW of 10 kHz, the capture time is 380 µs. The entire measurement, with a 4–6 MHz frequency span, an RBW of 6.25 kHz and 800 points can be digitized, processed using an FFT, decimated to one point per 6.25 kHz, and downloaded to the computer as often as five times every second.

A.2.1 Removing Impulsive Noise During a Measurement

During the acquisition, we may also capture impulsive noise; this algorithm attempts to minimize the acquisition of impulsive noise. Impulsive noise signals are also short in duration and quite prevalent in frequencies below 500 MHz where mobile assignments predominate. When measured using mobile IF bandwidths, impulsive noise can mistakenly be identified as mobile signals. Impulsive noise is generated by very short pulses originating from electrical machinery, automobile ignition systems, digital equipment, and electrical transmission lines [20]–[22].

This measurement algorithm computes a median of five traces at each frequency point, during a measurement of the frequency band. This median trace is then saved to the computer and data acquisition continues for a little more than one minute before moving to the next frequency band. Unless three or more of the five independent traces are contaminated by impulsive noise, the impulsive noise will be nearly eliminated by this processing step. Figure A-2 show the results of one median trace without the presence of impulsive noise and Figure A-3 shows the results of another median trace with the presence of impulsive noise. Figure A-2 shows a threshold level (green) and a trace showing the sample points acquired during measurements in the 164–169 MHz band (black rectangles). Because the sample points lie beneath the threshold level, any impulsive noise appears to be either absent from the measurement or removed through the FFT processing step. On the other hand, Figure A-3 shows trace sample points where more than 50% of the sample points rose above the threshold. For this plot, we would run an additional processing step to eliminate this trace because a certain percentage of the data in that trace is elevated more than 3 dB above a pre-determined threshold.

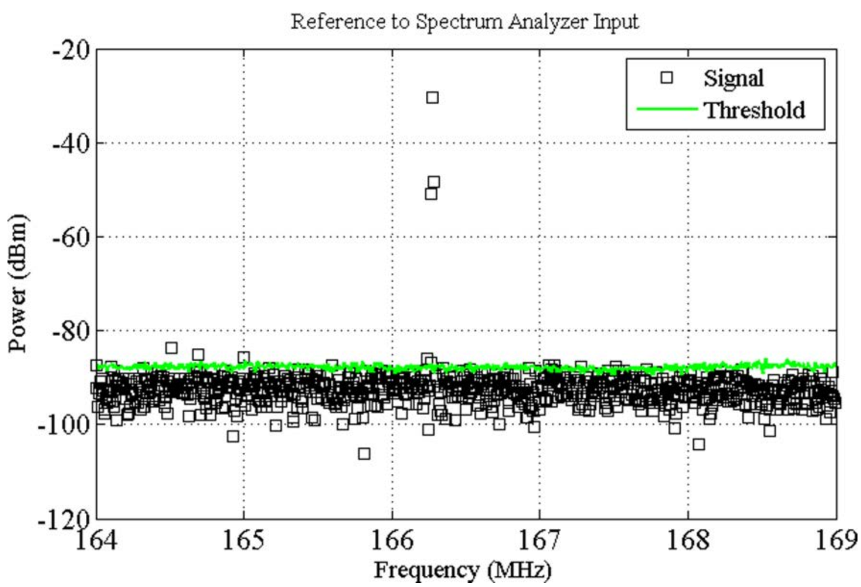

Figure A-2. Median-of-five processed trace—without RF impulsive noise.

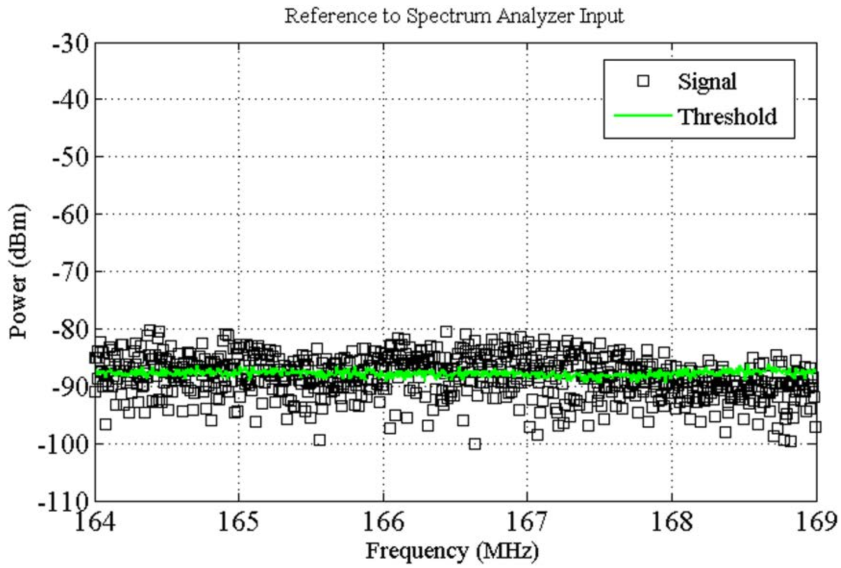

Figure A-3. Median-of-five processed trace——with RF impulsive noise.

A.2.2 Removing Impulsive Noise During the Post Processing Phase

When impulsive noise is still present in the acquired traces, an additional processing step can be used to minimize the display of impulsive noise in the final data sets. Impulsive noise shows up as horizontal lines as shown in Figure A-4 for the frequency range 159–164 MHz. The oblong rectangle shows one of these areas of impulsive noise.

This figure shows all data taken during the survey in this frequency band. In this band, there are only a few occurrences where impulsive noise appeared. To eliminate impulsive noise, we can examine each median trace taken during the survey and set a limit 3 dB above the threshold. Then we calculate a ratio of the samples above this limit to those below. We set a percentage elevation value for the number of points above this 3 dB limit. If we set this percentage elevation value to 50%, then we keep the trace if 50% of the samples are above this limit. Otherwise, we discard the trace and move to the next trace and perform the same analysis. We can set this percent elevation to any level and keep as much or as little of the data as possible. The data in Figure A-4 was processed using a percent elevation of 100%, so that all traces were kept for the display. In the waterfall plot, we notice that over 12,000 minutes of data were recorded.

If we process the data at both a 50% elevation level and a 15% elevation level, we obtain the two plots shown in Figures A-5 and A-6. We notice that at the 50% elevation level some of the impulsive noise has been removed and at the 15% elevation level most of the impulsive noise has been removed except for around 161.5 MHz. Also notice that the field strength level in the areas where the spectrum is devoid of signals in max trace in the top plot and the 0.09% trace in the bottom plot decrease as the percent elevation level decreases. This shows impulsive noise is being removed from the measurements.

Care must be taken, when using this technique, to avoid removing traces where valid signals also exist. This will be shown in Figures A-7 to A-13.

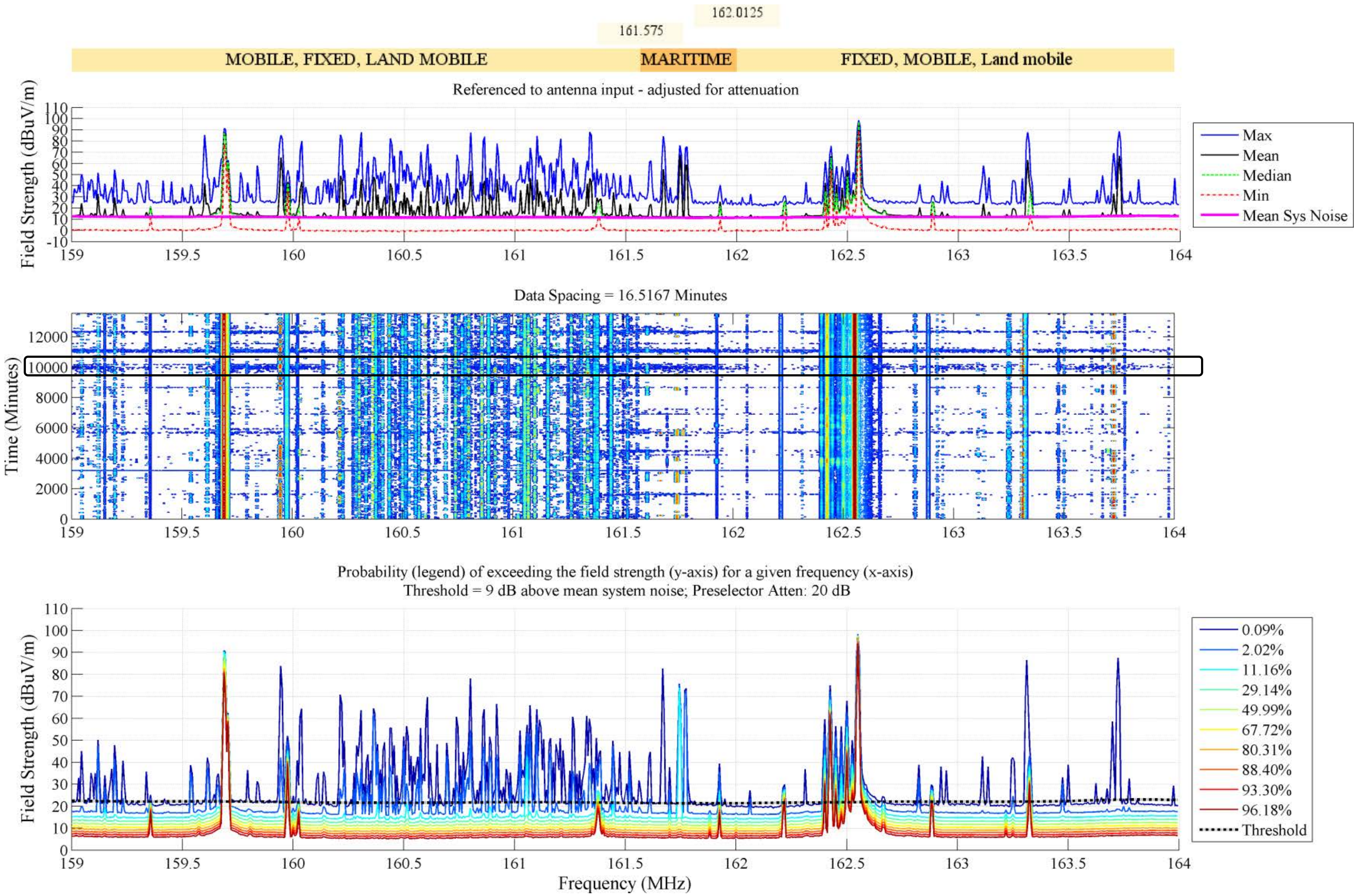

Figure A-4. Processed data from LMR band 159-164 MHz with a 100% elevation level. The rectangular box shows an area of impulsive noise.

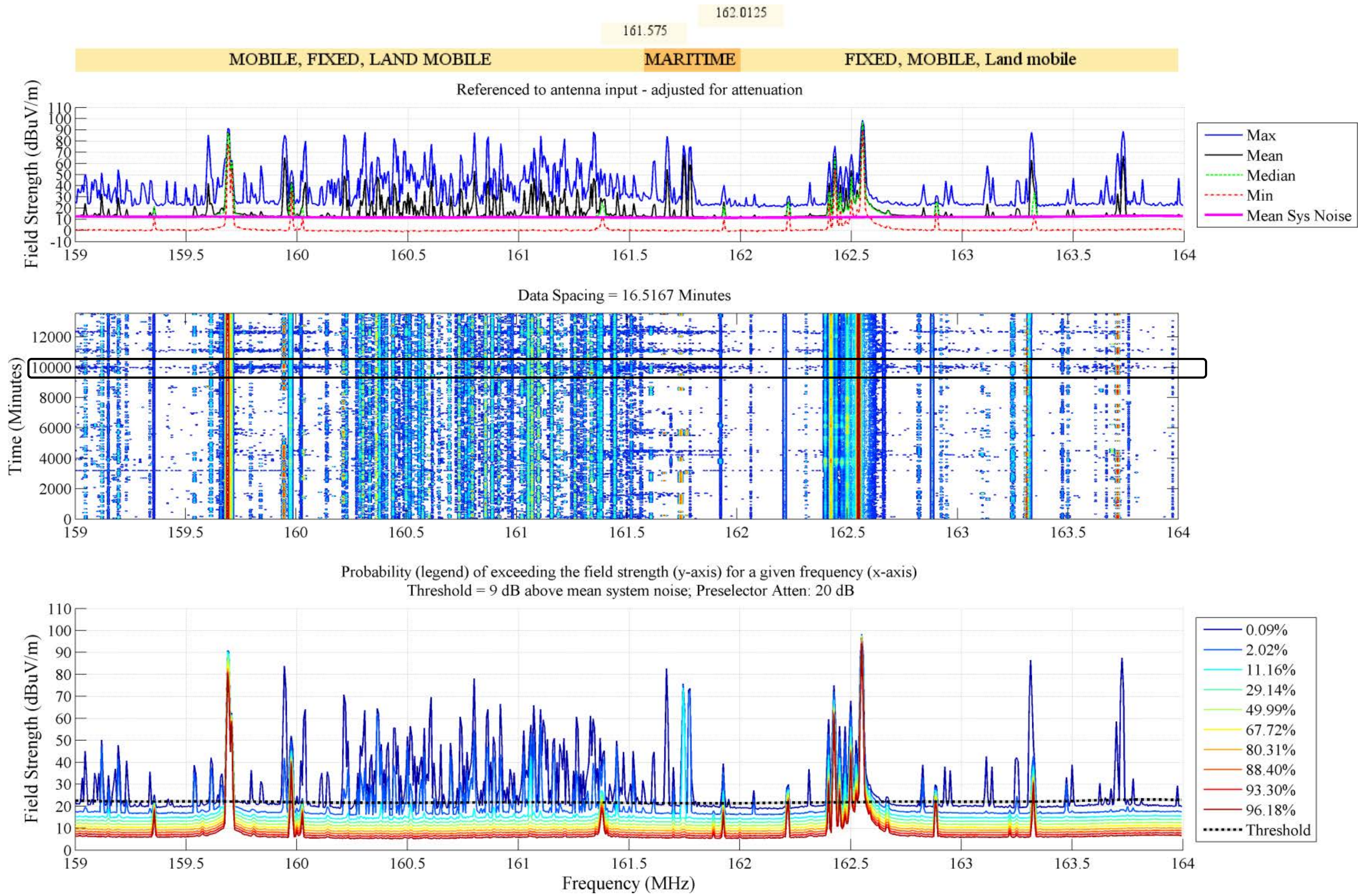

Figure A-5. Processed data from LMR band 159-164 MHz with a 50% elevation level. The rectangular box shows an area of impulsive noise.

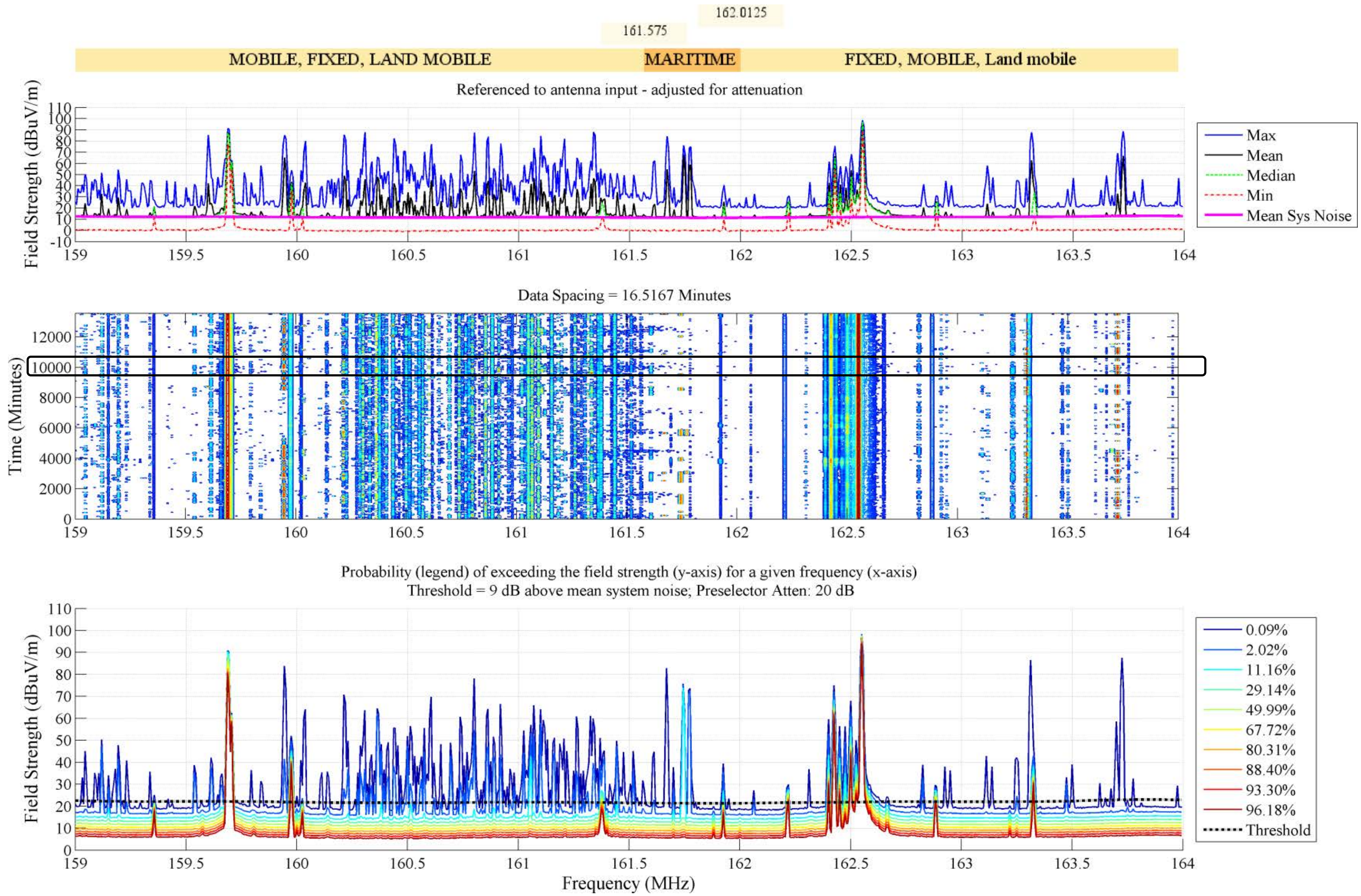

Figure A-6. Processed data from LMR band 159-164 MHz with a 15% elevation level. The rectangular box shows an area where impulsive noise was removed.

In Figures A-7 to A-13 we will look at the frequency range 138–143 MHz, which is an area of the spectrum that contains more impulsive noise than in the previous figures and where, if we are not careful about our processing, we will lose a lot of data using this post-processing technique. In Figure A-7, we have displayed all of the data taken in this frequency range during the survey. There are a couple of things to note: 1) the elevated field strength level for the max trace on the top plot and the elevated probability traces (0.09% to 29.14%) in the bottom plot, 2) the horizontal lines of data in the waterfall plot (middle plot) that tend to obscure some of the intentional signals in the band, and 3) the time axis on the waterfall plot showing the time in minutes. We observe that almost 14,000 minutes of data was taken during the survey in this frequency range. It is important to display the intentionally-emitted signals so that we can determine how active the band is; however, we must not lose sight of the fact that there is impulsive noise in this band which may affect certain receiving systems.

As mentioned above, we can experiment with various percent-elevation levels and we can also experiment with the threshold level. Figure A-8 shows data with a threshold level that is 9 dB above the mean system noise and at a 50% elevation angle. Notice how some of the field strength values in areas between the intentional emissions in the top and bottom plot are reduced from the values shown in Figure A-7. Also in the waterfall plot, the intensity of the horizontal lines has been reduced and some of the data has been eliminated so that the time axis is now reduced to a little over 12,000 minutes of data.

Figure A-9 shows data for a 9 dB threshold and a percent elevation level of 30%. In this plot, we have significantly reduced the noise present in the display, but we have also cut down the amount of data displayed by about half. The max trace field strength values and 0.09% trace levels have not changed much either. Figures A-10 and A-11 show data for a 9 dB threshold and percent threshold levels of 15% and 5% respectively. In Figure A-10, we have reduced the display of impulsive noise; however, we have also reduced the display of data to only 900 minutes and some of the important data from the survey has now been removed; with only a 5% elevation level, the data has been reduced to less than two hours, but the impulsive noise has almost been completely removed.

For this band, it would be better to increase the threshold level and use a percent elevation level that eliminates only a small portion of the really noisy data. By experimenting with this combination, we obtain the two graphs shown in Figures A-12 and A-13. In Figure A-12, the threshold level above mean system noise has been increased to 11 dB with a 15% elevation level and in Figure A-13, the threshold level above mean system noise has been further increased to 13 dB above mean system noise with a 15% elevation level. By comparing Figures A-10, A-12, and A-13, which are all at the same percent elevation level, we can see that as we increase the threshold level, we can retain most of the data from the spectrum survey and minimize display of impulsive noise.

For the current set of survey reports, the data presented attempts to minimize the display of impulsive noise in frequencies below 500 MHz by adjusting the threshold level, when needed, and using a percent elevation level of 50% for most of the frequency bands.

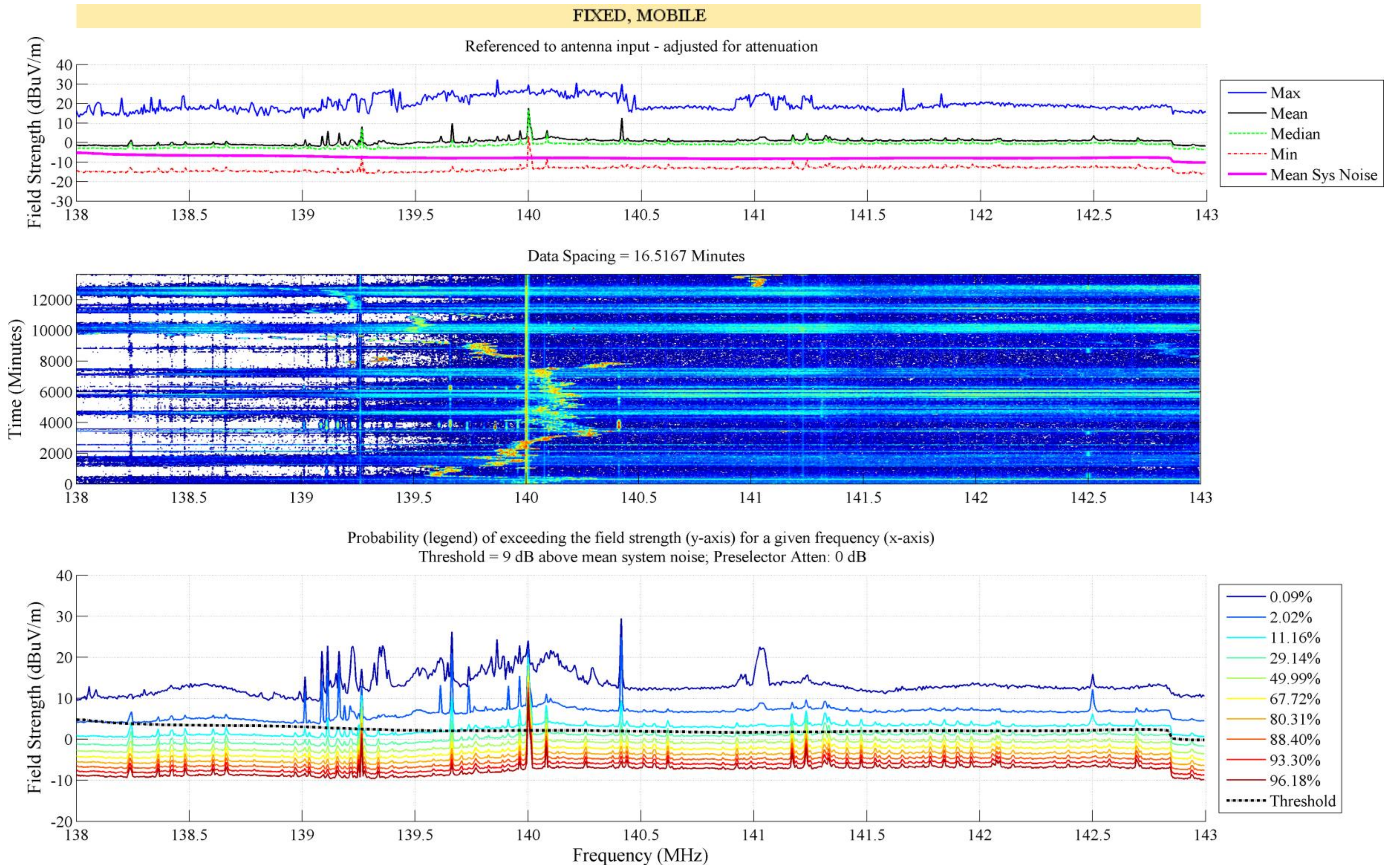

Figure A-7. Processed data from LMR band 138-143MHz with a 100% elevation level at a threshold level of 9 dB above mean system noise. This processing level includes all measured data.

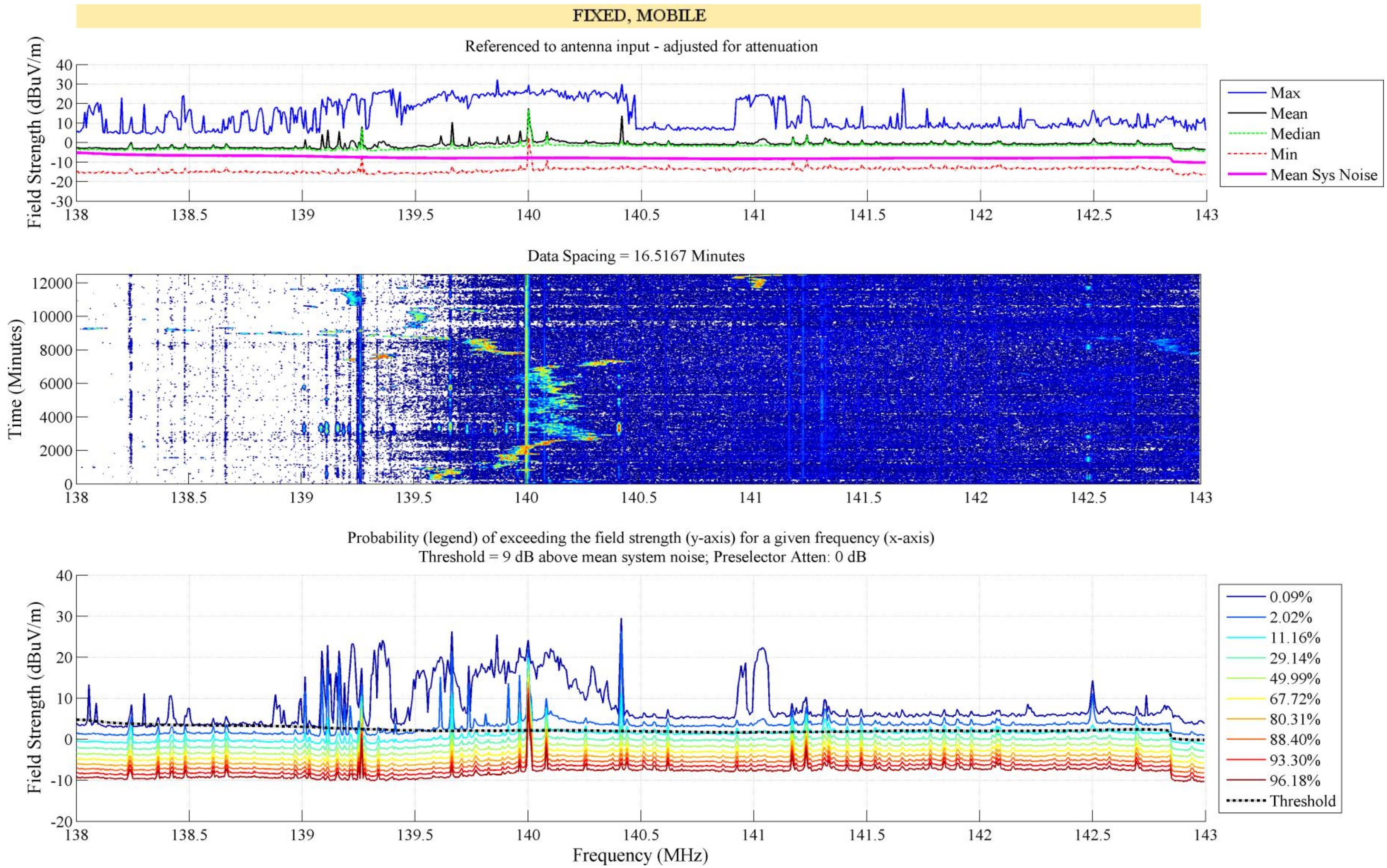

Figure A-8. Processed data from LMR band 138-143MHz with a 50% elevation level at a threshold of 9 dB above mean system noise.

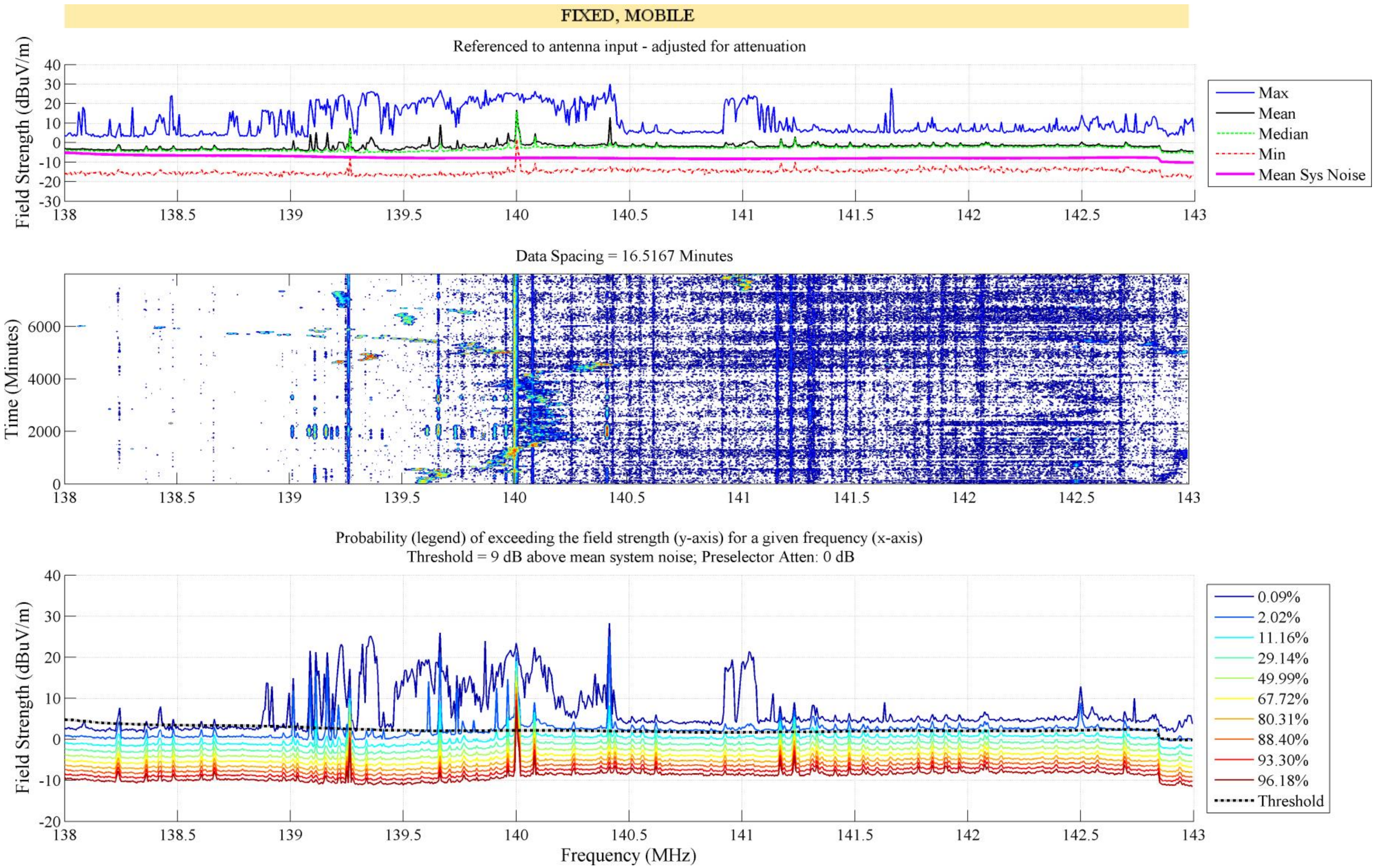

Figure A-9. Processed data from LMR band 138-143MHz with a 30% elevation level level at a threshold level of 9 dB above mean system noise.

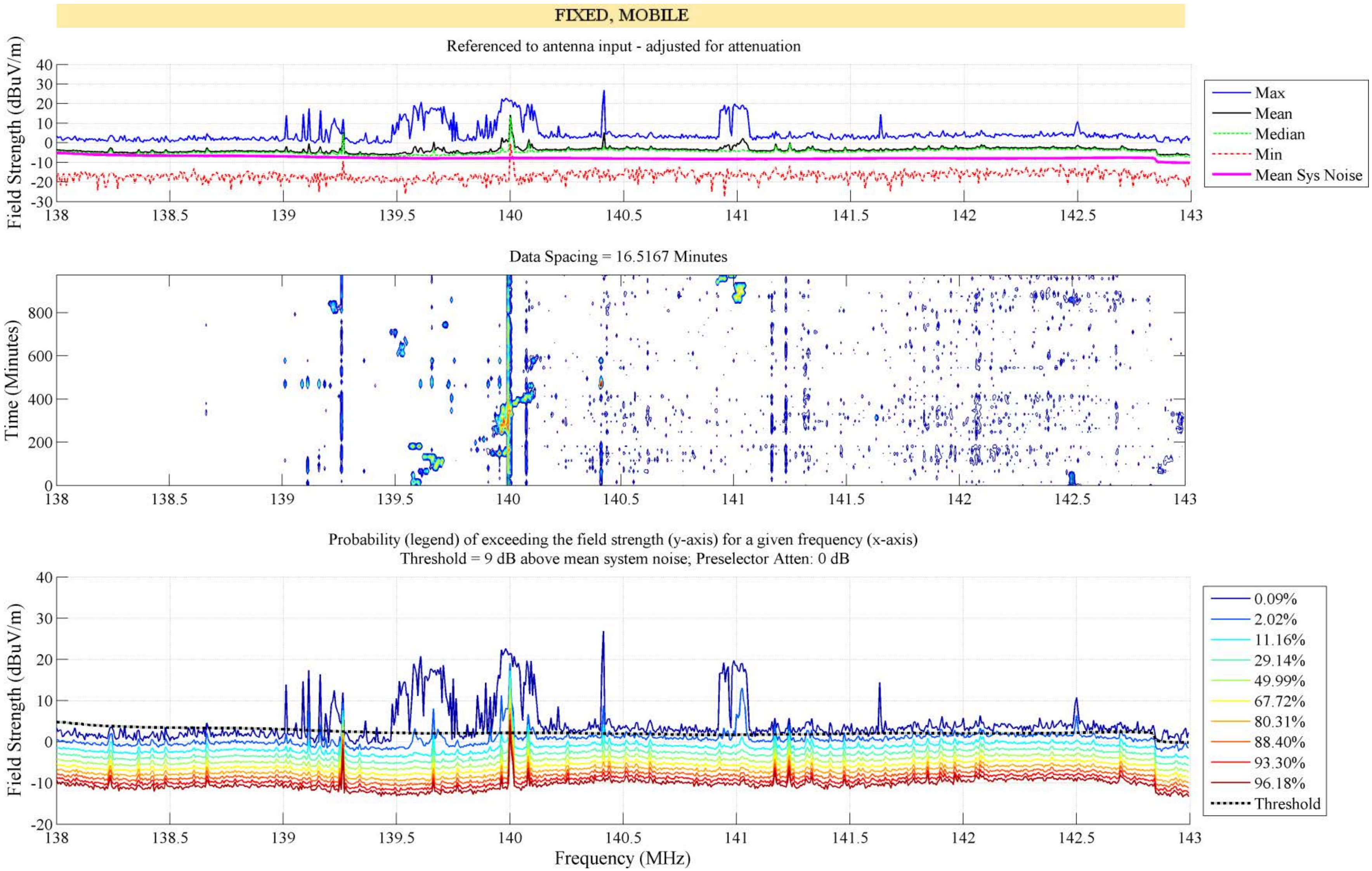

Figure A-10. Processed data from LMR band 138-143MHz with a 15% elevation level level at a threshold level of 9 dB above mean system noise.

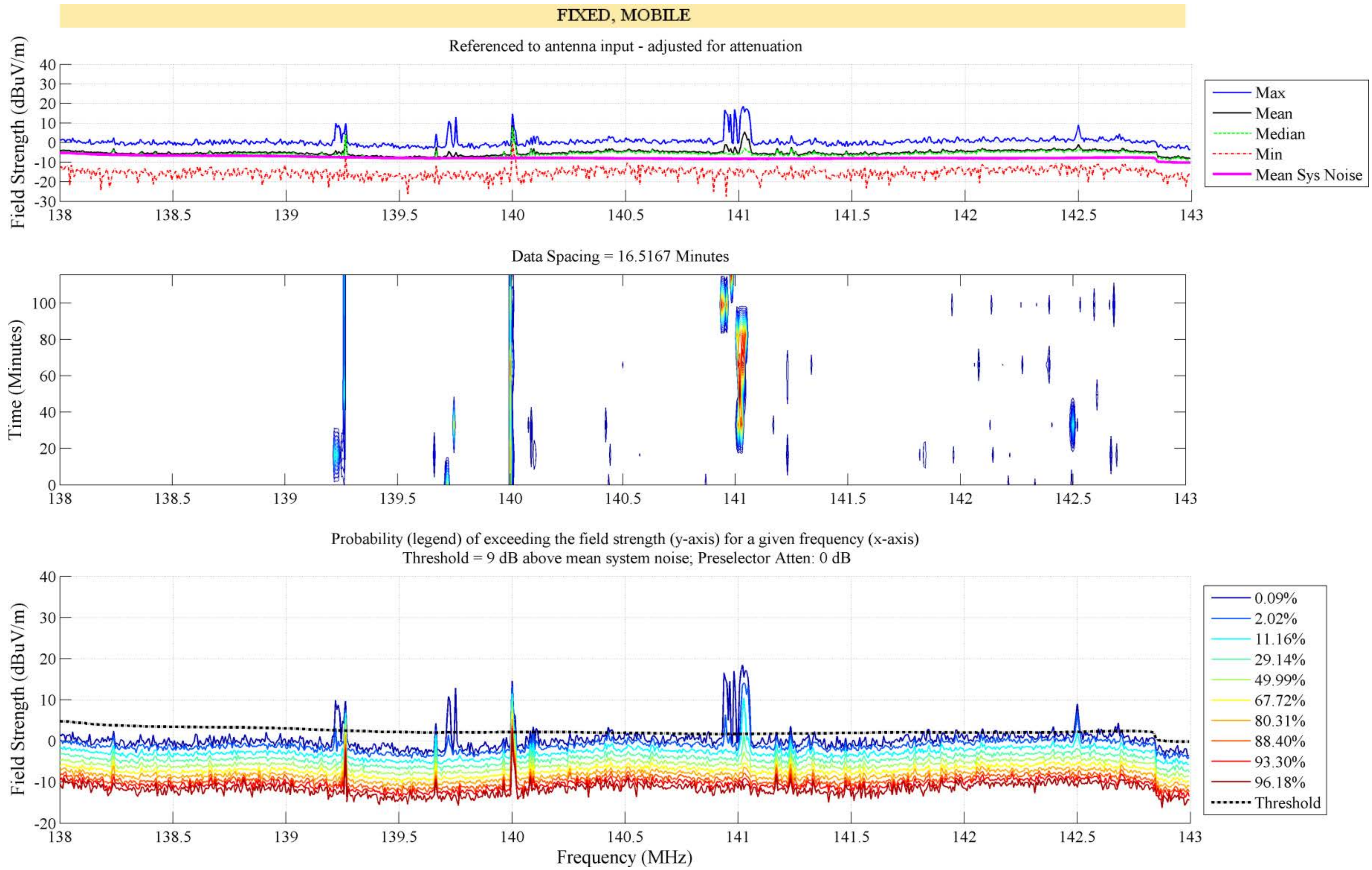

Figure A-11. Processed data from LMR band 138-143MHz with a 5% elevation level level at a threshold level of 9 dB above mean system noise.

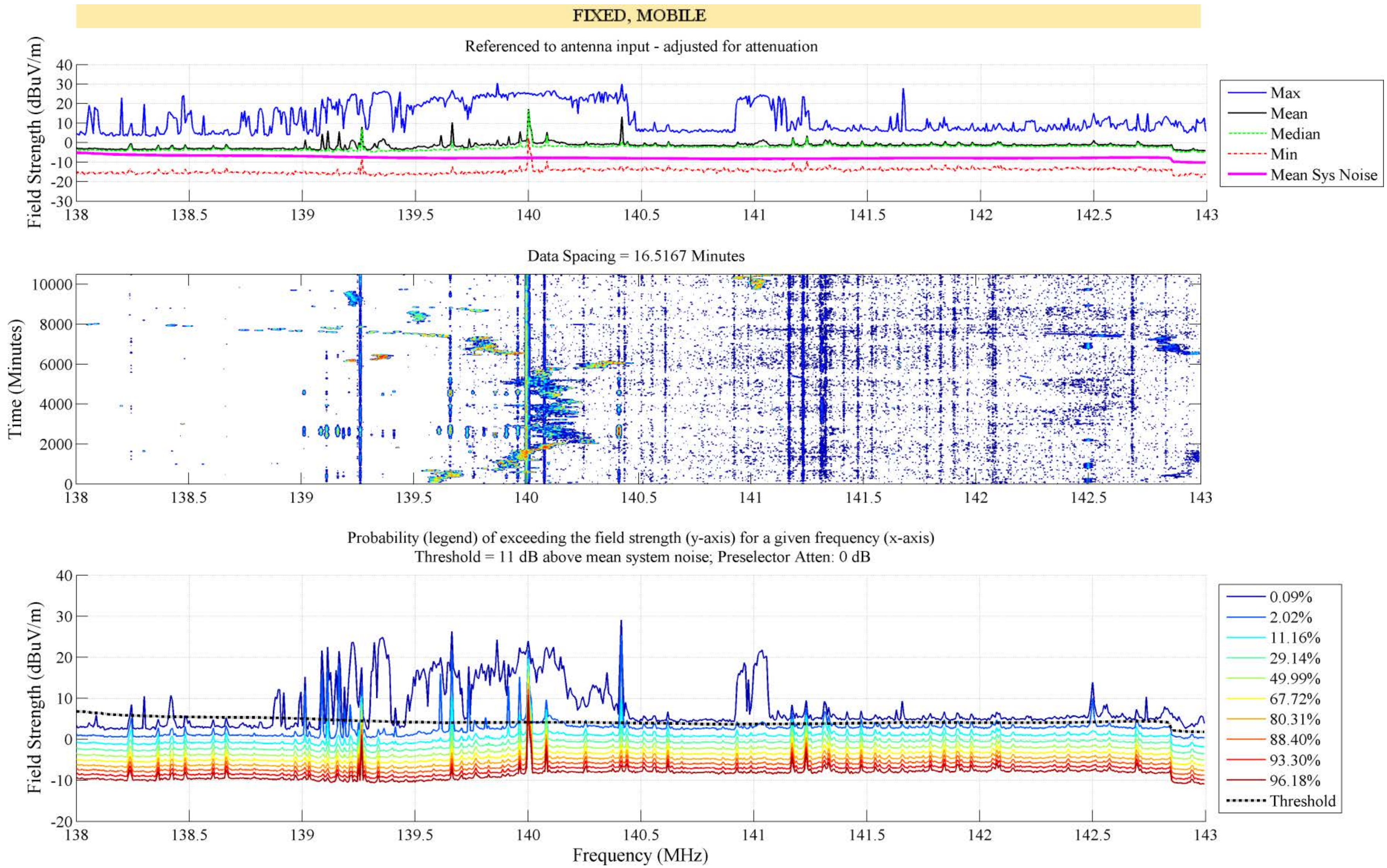

Figure A-12. Processed data from LMR band 138-143MHz with a 15% elevation level at a threshold value of 11 dB above the mean system noise.

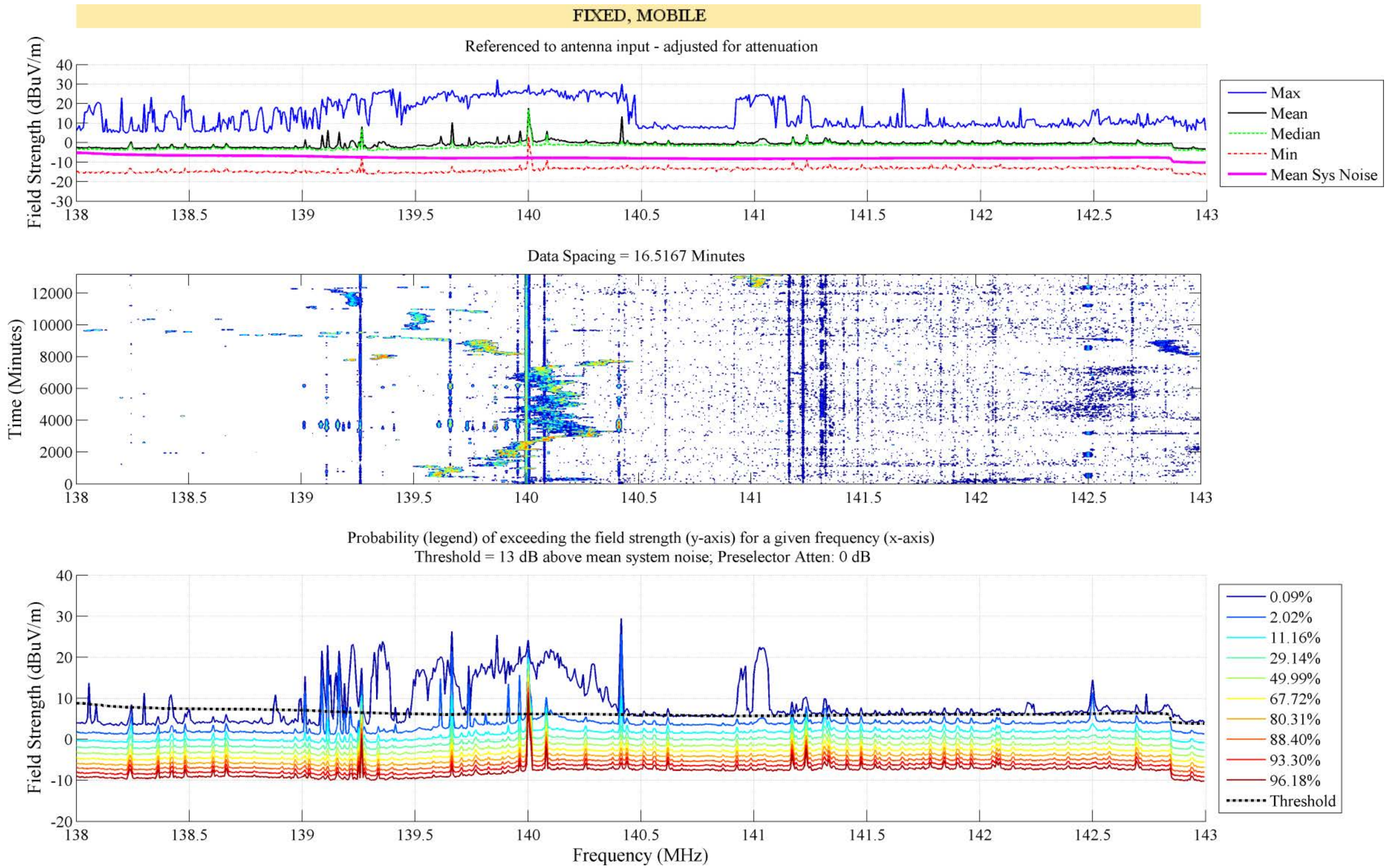

Figure A-13. Processed data from LMR band 138-143MHz with a 15% elevation level with a threshold value of 13 dB above the mean system noise.

FORM **NTIA-29**
(4-80)

U.S. DEPARTMENT OF COMMERCE
NAT'L. TELECOMMUNICATIONS AND INFORMATION ADMINISTRATION

BIBLIOGRAPHIC DATA SHEET

1. PUBLICATION NO.	2. Government Accession No.	3. Recipient's Accession No.
TR-14-502		

4. TITLE AND SUBTITLE Broadband Spectrum Survey in the Chicago, Illinois, Area	5. Publication Date April 2014 6. Performing Organization Code NTIA/ITS.M
7. AUTHOR(S) Chriss Hammerschmidt	9. Project/Task/Work Unit No. 3154012-300
8. PERFORMING ORGANIZATION NAME AND ADDRESS Institute for Telecommunication Sciences National Telecommunications & Information Administration U.S. Department of Commerce 325 Broadway Boulder, CO 80305	10. Contract/Grant Number.
11. Sponsoring Organization Name and Address National Telecommunications & Information Administration Herbert C. Hoover Building 14th & Constitution Ave., NW Washington, DC 20230	12. Type of Report and Period Covered

14. SUPPLEMENTARY NOTES

15. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

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 Chicago, Illinois, during a two week period in September 2012.

16. Key Words (Alphabetical order, separated by semicolons)
land mobile radio (LMR); radar emission spectrum; radio spectrum measurement system (RSMS); radio frequency environment; spectrum occupancy; spectrum resource assessment; spectrum survey

17. AVAILABILITY STATEMENT	18. Security Class. (This report)	20. Number of pages
☒ UNLIMITED.	Unclassified	155
☐ FOR OFFICIAL DISTRIBUTION.	19. Security Class. (This page) Unclassified	21. Price:

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