L and S Bands Spectrum Survey in the San Francisco Bay Area

Juyong Do, Dennis M. Akos, Per K. Enge

***Abstract*- The Global Positioning System (GPS) is a radio frequency (RF) navigation system that consists of transmitters on the satellites and receivers on the ground. Because of substantial path loss, the received signal power from the satellites is relatively weak, even below the thermal noise floor and as such is very sensitive to changes in the underlying noise floor. The goal of this work is to investigate the radio spectrum environment in the GPS band along with two additional bands, the Unified-S band and 2.4 GHz Industrial Scientific and Medical (ISM) band. These frequency bands are allocated for the different applications and thus, are under the different level of regulations and the study in these rather different bands would help to understand the impact of the applied regulations on the actual spectral environment and investigate the effectiveness of the current spectrum policy in the GPS band. The spectrum survey was conducted at various locations in the San Francisco Bay area including various urban and rural areas as well as airports and harbors which are operationally significant to GPS. The total eight survey sites were selected to obtain the geographically diverse measurement results and could provide a more general representation of the spectral environment and possibly site-to-site trends.**

***Index Terms*- Spectrum survey, spectral environment, thermal noise floor, GPS, ISM, Unified-S band**

I. Introduction

As always, new wireless technologies seek radio spectrum for development, operation and expansion. As part of such movements, there is growing interest in increasing allocations for unlicensed spectrum use which brings concerns about degradation of the radio spectrum environment to existing allocations. Thus the assessment of the current status and forecasting the future of the spectral environment becomes important. This study supports efforts to understand and quantify the current operational environment of radio systems and develop a scientific basis for further studies on changes of the spectral environment.

In this report, we compared actual radio frequency power measurements to the power due to natural thermal noise alone. The power density due to natural thermal noise is the product of the Boltzmann's constant and the so-called noise temperature in Kelvin (kT_O). The noise power in a given bandwidth (B) is the noise power density times the bandwidth (kT_OB). In bands used by satellite services, the total measured power should be close to the natural noise floor. After all, the satellites are significantly far away with relatively low output levels and so the received signal power is low. In bands used by terrestrial services, the total measured power may be quite high relative to the natural noise floor.

We included three rather different radio bands in this study described in the Table I. First, we studied the L1 band used by the Global Positioning System. GPS provides a safety critical service from space. The GPS signal is broadcast from a constellation of some 29 satellites (in January of 2004) that are in medium Earth orbit (MEO). The satellites have an altitude of 20,200 km, which provides global coverage. However, the received signal has low power, because of the path loss. On the Earth's surface, the GPS signal power is below that of the natural noise floor.

Second, we studied the Unified S band used by the National Aeronautics and Space Administration (NASA) to uplink and downlink data from space. Electronic news gathering (ENG) also uses the Unified S band. As such, the Unified S band is shared between terrestrial and space use.

Third, we studied the 2.4 GHz band that is allocated for unlicensed use by industrial, scientific and medical (ISM) use. This band is finding increased use for unlicensed wireless technologies such as wireless networks and cordless telephones. It also contains radio energy from microwave ovens. The open nature of the ISM band means that applications will vary, but terrestrial users are likely to be present anywhere and anytime.

TABLE I
FREQUENCY BANDS UNDER STUDY

Band	Center Frequency	Band-width	Allocation	Regulatory Part
GPS L1	1575.42 MHz	24 MHz	Aero-RadioNav Radionav-Sat.	Aviation Part 87
UNI-S	2067.5 MHz	85 MHz	Space Science Aux Broadcast	Part 74F, Part 78, and Part 101J
ISM 2.4	2441.75 MHz	83.5 MHz	Fixed & Mobile Radiolocation Amateur	Part 18 and Part 97

Our three bands find diverse use. The GPS band is for signals from space to thirty million (or so) users all over the globe. The Unified S band serves a finite number of fixed sites with satellite signals, and then a limited number of terrestrial users. The ISM band serves an enormous number of terrestrial users that may be found anywhere. To support their diverse uses, the corresponding regulations are quite different between the frequency bands. The GPS L1 band is relatively well protected for the navigation systems from other types of applications because of its criticality to the transportation systems and the magnitude of the user community. The Unified S band is also well protected for the NASA mission but the ENG services are allowed in the band. The ISM band is virtually open to most of applications and therefore each application needs to assume the competition from the rest of applications sharing the band.

Because of the difference between the frequency bands under study, the spectrum survey will be an interesting observation. The spectral environment could be noisy in the 'open' band like the ISM band and quiet in the 'protected' band like the GPS band because of the enforced regulations as generally believed. But there are also concerns about increased noise level even in the protected bands regardless of the regulations due to the proliferation of the man-made electronic equipments. In other words, there is a raised question about the effectiveness of the current spectrum policy to protect the allocations and prohibit the unregulated use of the spectrum. The discussion about the spectrum policy will be out of the scope of this paper but the observation made in this study could help to address such concerns.

The spectrum survey was initiated on August 28th, 2003 and continued until November 15th, 2003 through the autumn season in the moderate weather conditions. The radio power spectrum was measured in these three bands at a variety of sites which are divided into the 4 categories: urban areas, rural areas, airports and harbors. Two of the sites are downtown in San Jose and Palo Alto. Two sites were remote from thickly settled areas - Yosemite Park and the Jasper Ridge Preserve. Two sites are at airports (San Jose and Palo Alto). Two sites are at harbors or marinas (Port of Oakland and Coyote Point Marina). All sites are listed and numbered in Table II with the survey schedule and their locations are shown in Fig 1. The numbers in Table II are used to identify the sites in the Fig 1.

All of these sites are operationally significant to GPS. Indeed, GPS helps coordinate police and fire efforts in urban areas like San Jose and Palo Alto. It is also an important part of the transportation systems in cities. GPS is being integrated into an increasing fraction of cell phones. In some parts of the country, GPS provides the position information that is automatically relayed when cell phone users call 911. GPS is also critical in rural areas. It is finding increased application in precision farming and mining. Of course it is an important navigation aid for hikers. Clearly, GPS is important to aviation and therefore critical in the airport environment. Indeed, GPS is included on every new Boeing jet and finds widespread use in regional carriers and general aviation. With the July 10, 2003 commissioning of the Wide Area Augmentation System, GPS is used during the approach procedure as well as enroute flight. Finally, GPS is the primary position-fixing tool used by ships during harbor and harbor entrance navigation. The U.S. Coast Guard maintains a network of DGPS radiobeacons to augment these critical operations.

TABLE II
MEASUREMENT SITES AND SCHEDULES

Index	Category	Site	Date	Time (hours)
1	Urban I	San Jose Downtown	Oct 21 ~ 22	24
2	Urban II	Palo Alto Downtown	Nov 5 ~ 6	24
3	Rural I	Yosemite Park	Nov 14 ~15	24
4	Rural II	Jasper Ridge Preserve	Oct 9 ~ 10	24
5	Airport I	San Jose Airport	Oct 7 ~ 8	24
6	Airport II	Palo Alto Airport	Sep 4	16
7	Harbor I	Port of Oakland	Oct 30	15
8	Harbor II	Coyote Point Marina	Aug 28	16

Fig 1.Measurement sites (via www.mapquest.com)

In summary, this report contains a matrix of measurements. We measured the radio spectrum in the three bands that serve very different purposes at eight diverse sites and contrasted the measured power to the theoretical value for the natural thermal noise (kT_O) and identified site-to-site trends.

II. TEST METHODOLOGY

A multi-band instrument was built for the radio power spectrum measurement campaign in the GPS L1 band, the Unified S band, and the 2.4 GHz ISM band. The instrument is called the L and S band Spectrum Measurement system (LSSM). It has a customized multi-band front end design combined with a spectrum analyzer. The data collection process is automated using a notebook PC and Labview instrument control software to minimize the possibility of human error and provide repeatability in the data collections. The block diagram of LSSM is shown in Fig 2.

Two horn antennas, a GPS antenna and a 50 ohm reference load are used as signal inputs to the system. The three antennas are used to measure radio power (natural noise plus the man-made signals). The two horn antennas are used to azimuthally localize any man-made signals. The first horn antenna is horizontally oriented to capture the horizontally polarized signal and the second horn antenna is vertically oriented to capture the vertically polarized signal. The GPS antenna has a nearly hemispherical pattern directed skyward like an operational GPS antenna. The 50 ohm reference load is used for a reference measurement approximately equal to the natural noise floor. It is used to validate the health of the antenna measurements.

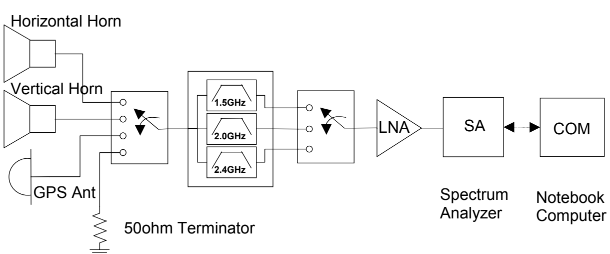

Fig 2. L and S band spectrum measurement system (LSSM)

The LSSM front end includes: three custom cavity bandpass filters, a low noise amplifier (LNA) and two RF switches used to route the signal inputs. The RF switches are used to implement a fully automatic measurement system, which operates without any human intervention during the measurement campaign. The design is a mechanical relay type switch with fairly low loss (< 0.2 dB) and low impact on the noise figure. The filter bank is located prior the LNA to remove out-of-band-emissions (OOBE) from the measurements and prevent LNA signal saturation. The cavity filters have low insertion loss (< 1.0 dB). The overall loss caused by the two RF switches and the filter bank is less than 1.4 dB. The overall gain of the LSSM front end is approximately 37 dB and the noise figure is approximately 3 dB.

Our procedure measures the radio environment over the course of a full day including early morning and late night (in a few cases, logistics prevented measurements after midnight). The measurement cycle starts early in the morning and is repeated every hour. During one measurement cycle, three frequency bands: GPS L1, UNI-S and ISM 2.4, are monitored and four signal inputs: the horizontal horn, the vertical horn, the GPS antenna and the 50 ohm reference load are used. With the directive horn antennas, the LSSM rotates with a 15 degree step and measures the power spectrum at 24 angular points.

The collected data delivers information about radio spectrum environment in different domains: time, frequency, angle and statistics. We could find the signal variation over time and seek any correlation between the received power and the ebb and flow of human activities through the day. In frequency domain, the power spectrum of the measured signals reveals the power, bandwidth and center frequency of any man-made signals that are in band. In angular domain, the direction of any man-made signals could be identified and we can examine the photograph taken in that direction by the installed digital camera on the LSSM. Finally, the statistical analysis shows the power histogram of the measured signal. Any deviation from the distribution for thermal noise would suggest a man-made radio signal. The histogram estimates the probability of the man-made signals at the measurement site.

III. RESULTS

The spectrum survey was conducted in the three bands at the eight sites and provided a matrix of measurements. We present and analyze the collected data within a band to compare to the thermal noise floor (kT_0) and investigate the site by site trends. For analysis of the measurement data, we use four methods: the average power spectrum, the average and the standard deviation of the measured power in dBm/MHz and the estimated percentage of the man-made signals among the measurement data. When these average and variance analyses are combined, the statistical distribution of the radio power spectrum can be described. The thermal noise floor at room temperature, 296 K, is approximately -114 dBm/MHz and the noise figure of LSSM is approximately 3 dB. Therefore the average power spectrum and the average of the measured power should be close to -111 dBm/MHz when there are no man-made signals. The amplitude of natural thermal noise follows Gaussian distribution and thus its signal power exponentially distributed and the standard deviation is expected to be the same as the average. The percentage of the man-made signals among the measurement data, containing both the natural thermal noise and the man-made signals, could be estimated by comparing the distribution of the measured data and the theoretical distribution of the natural noise. A threshold was established to discern the man made signal which is the average of the natural noise plus 10 dB. Since the percentage of data higher than this threshold is less than 0.005 % without any man-made signals, we can declare results higher than the threshold value as the man-made signal with statistical confidence. Further, the percentage is used as a ratio of the man-made signal in the measurement data.

A. GPS L1 Band

The thermal noise floor is proportional to the ambient temperature. In case of directional antenna designs, such as horn antennas used in this study, the effective ambient temperature depends on temperature of the object which the antennas are directed toward. If it is directed to the earth, the thermal noise floor will be proportional to the earth temperature, 296 K and if it is directed to the sky, proportional to the sky temperature, approximately 100 K. The ambient thermal noise is added to the receiver intrinsic noise and forms the receiver noise floor. In this study the horn antennas are directed to the horizon and thus, they observe the sky and the earth at the same time and the effective ambient temperature will be between the earth temperature and the sky temperature. In Fig 3, the measured power spectrum is compared to the expected thermal noise floor. The two straight lines represent each the expected receiver noise floor assuming the earth temperature and the sky temperature respectively and the curve is the measured power spectrum in the GPS L1 band.

Clearly, the measured power spectrum is in the middle of the two theoretical lines as expected. At the center of the band, there is little rise from the background noise floor which is the GPS signal. The GPS signal from the individual GPS satellites is approximately 15 dB lower than the thermal noise floor but the collective signal powers combined with antenna gain provide sufficient spectral detection capabilities and can be observed above the noise floor as shown in Fig 3.

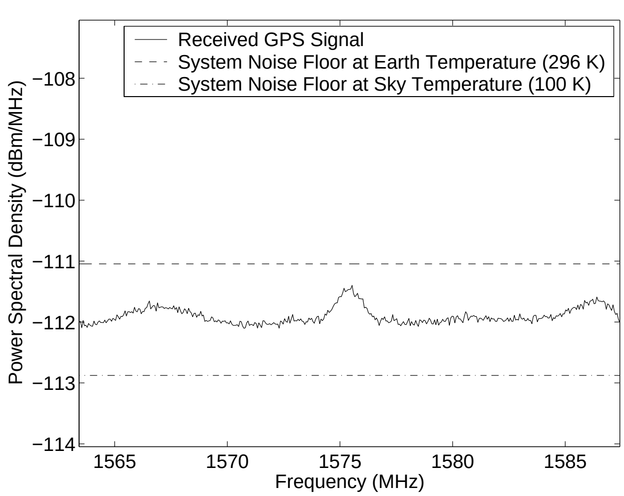

Fig 3.Spectrum measurement of GPS L1 signal

In all measurement sites, we observed the background thermal noise floor in most of cases and there were very rare appearances of the man-made signals.

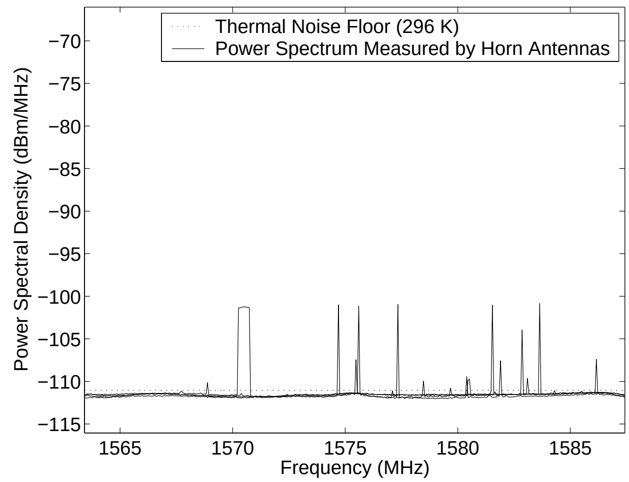

Fig 4.Spectrum measurement at urban sites in GPS L1 band

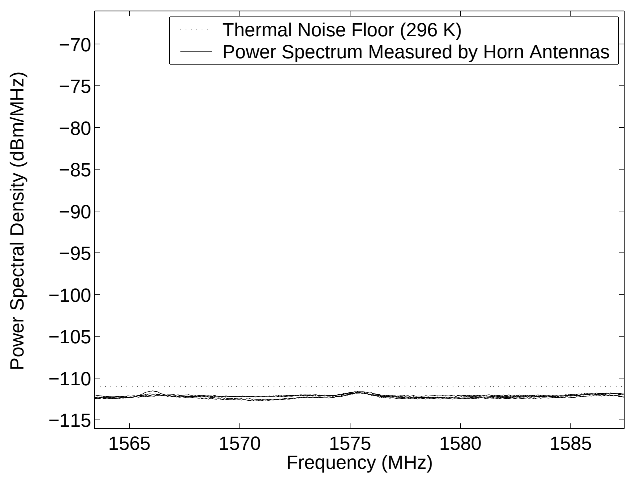

Fig 5.Spectrum measurement at rural sites in GPS L1 band

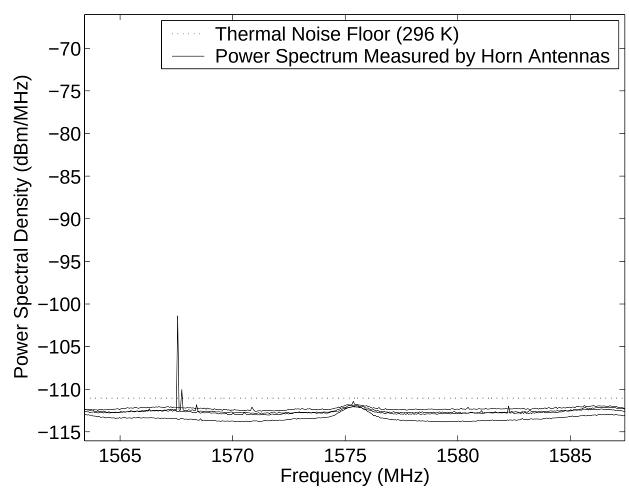

Fig 6.Spectrum measurement at airport sites in GPS L1 band

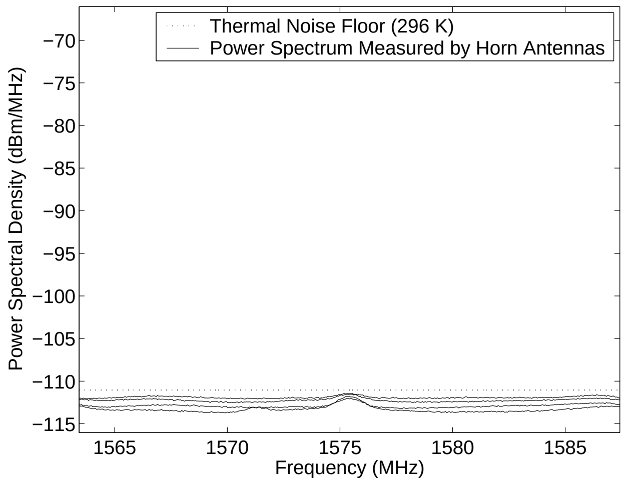

Fig 7.Spectrum measurement at harbor sites in GPS L1 band

The average received power was approximately equal or less than the thermal noise floor. In Fig 4~7, the average power spectrum measured for 15 hours to 24 hours are presented in power spectral density (dBm/MHz) versus frequency (MHz). The dotted line is the thermal noise floor assuming 296 K and the solid lines are the measurements by the two horn antennas. The measurements by the GPS antenna are not displayed separately because they are nearly identical to the measurement by the horn antennas and there were no man-made signals detected by the GPS antenna. Data are displayed per each category.

In the urban sites the man-made signals were shown in several frequency ranges in the band. They were narrow band signals with the bandwidth less than 1 MHz and observed from a nearby building only for a short instance and in the rest of time periods, there were no detected man-made signals. Similar types of the man-made signals were observed in the airport sites which also happened for a short instance. In the rural and harbor sites, there was no detection of any man-made signals.

The statistical analyses are summarized in Table III. Each row represents the result from the each site and the analyses are divided into three section: the average and the standard deviation of the measured power in dBm/MHz and the estimated percentage of the man-made signals among the measurement data. Each analysis includes the results from the measurement by the different antennas: the horizontally oriented horn antenna, the vertically oriented horn antenna, the GPS antenna and the 50 ohm reference load which are abbreviated as 'HOR', 'VER', 'GPS' and '50 ohm' respectively. For all sites, the average received power was lower than -111 dBm/MHz and the standard deviation was close to the average except the urban sites and the airport I site which contained man-made signals. Specifically, the estimated percentage of the man-made signals are less than 0.02 % for all sites but slightly higher in sites where the man-made signals were detected.

TABLE III
STATISTICAL ANALYSIS OF DATA IN GPS L1 BAND

Site	Average [dBm/MHz]				Standard Deviation [dBm/MHz]			Percentage of Man-Made Signal [%]		
	HOR	VER	GPS	50 ohm	HOR	VER	GPS	HOR	VER	GPS
Urban I	-111.0	-111.7	-112.0	-111.6	-89.9	-101.3	-112.1	0.01	0.01	0.01
Urban II	-111.5	-110.7	-111.2	-111.7	-112.0	-88.9	-109.1	0.00	0.02	0.01
Rural I	-112.1	-112.3	-112.5	-111.9	-112.8	-113.0	-113.2	0.00	0.00	0.00
Rural II	-112.1	-112.3	-112.2	-111.8	-112.8	-113.0	-112.9	0.00	0.00	0.00
Airport I	-112.5	-113.4	-112.8	-111.7	-93.9	-113.6	-113.4	0.01	0.00	0.00
Airport II	-112.3	-112.7	-112.5	-111.7	-111.4	-112.8	-113.0	0.00	0.00	0.00
Harbor I	-112.9	-113.3	-112.9	-111.7	-113.6	-113.4	-113.5	0.00	0.01	0.00
Harbor II	-111.9	-112.2	-112.3	-111.4	-112.6	-112.9	-112.9	0.00	0.00	0.00

B. Unified S Band

The Unified S band is found to be quiet in the rural sites and noisy in the urban sites.

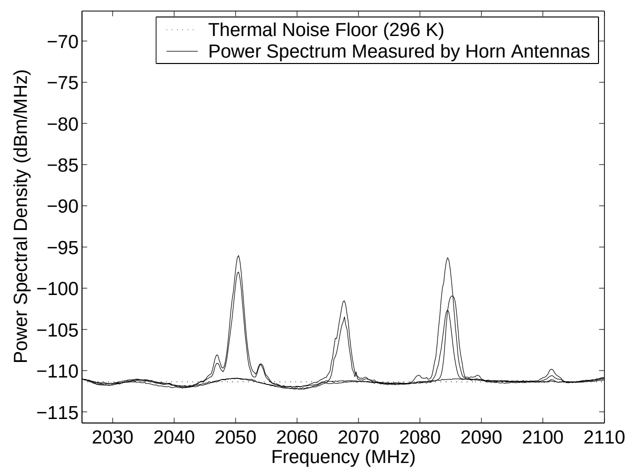

Fig 8.Spectrum measurement at urban sites in Unified S band

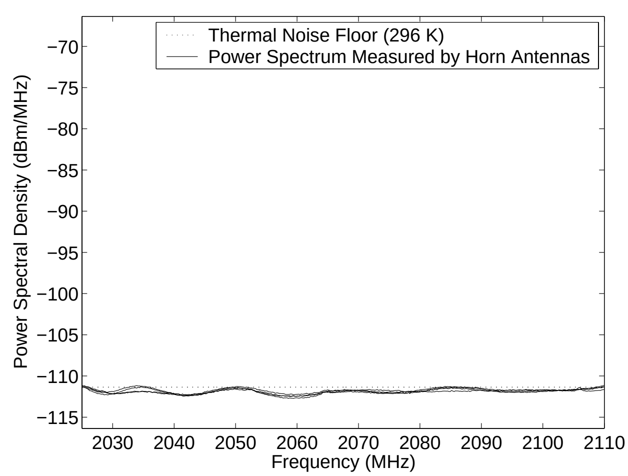

Fig 9.Spectrum measurement at rural sites in Unified S band

The detected man-made signals are presumed to have been transmitted from remote television sources. Again, the Unified S band is used for the electronic news gathering service (ENG) by TV news vans. All detected signals were located at a specific set of frequencies and excluding these left no other distinguishable man-made signals observed. The measured power was highly dependent on the proximity to the downtown area where more television operations are expected to be in use.

In Fig 8 and 9, the average power spectrum is displayed. First, in the urban sites the man-made signals were shown in three uniformly distributed frequencies. They were rather wide band signals with the bandwidths of approximately 5 MHz and observed from various locations in higher levels from evening to early morning. The measured man-made signals were mainly found at the specific set of frequencies, 2050, 2068 and 2085 MHz. However, in the rural sites, no man-made signal was detected.

The statistical analyses are summarized in Table IV. In the urban I site, the average received power was higher than -111 dBm/MHz and the standard deviation was also high indicating the existence of the man-made signals. In the urban II site, the man-made signals was observable although they were in lower power level. The rural sites remained quiet in power lower level less than -111 dBm/MHz. The estimated percentage of the man-made signals rose as high as 1.67 % in sites where the man-made signals were detected.

TABLE IV
STATISTICAL ANALYSIS OF DATA IN UNI-S BAND

Site	Average [dBm/MHz]			Standard Deviation [dBm/MHz]		Percentage of Man-Made Signal [%]	
	HOR	VER	50 ohm	HOR	VER	HOR	VER
Urban I	-109.2	-107.9	-111.4	-101.6	-98.4	1.35	1.67
Urban II	-111.4	-110.6	-111.5	-112.0	-96.8	0.01	0.06
Rural I	-111.8	-111.9	-111.6	-112.5	-112.6	0.00	0.00
Rural II	-111.7	-111.9	-111.5	-112.4	-112.6	0.00	0.00

C. ISM 2.4 GHz Band

At all measurement sites, the average received power was well above the thermal noise floor in the ISM 2.4 GHz band. There were significant levels of the man-made signals regardless of time and location showing the proliferation of unlicensed devices in ISM 2.4 GHz.

In Fig 10 and 11, the average power spectral density is displayed. In the urban sites the man-made signals were shown to completely occupy the band. They are indistinguishable from one another with tight overlapping and were observed from all directions for all time periods. Similar types of the man-made signals were observed even in the rural sites. However, even within this band there was still an observable difference between the rural sites and the rest of sites. In the rural sites, the man-made signals were either time limited or space limited. In other words, the signal sources of those man-made signals operated only during short time frames or those signals were observed from specific directions. The detected man-made signals sources at the rural sites were one or two nearby identifiable objects while those at the other sites resulted from substantial numbers of unknown objects which operate regardless of time of day.

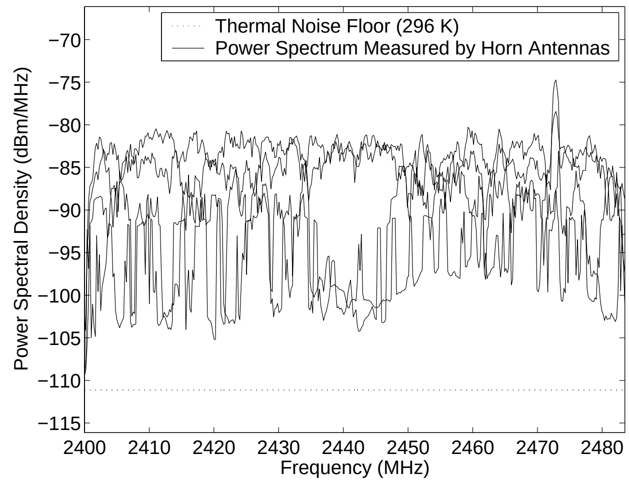

Fig 10.Spectrum measurement at urban sites in ISM 2.4GHz band

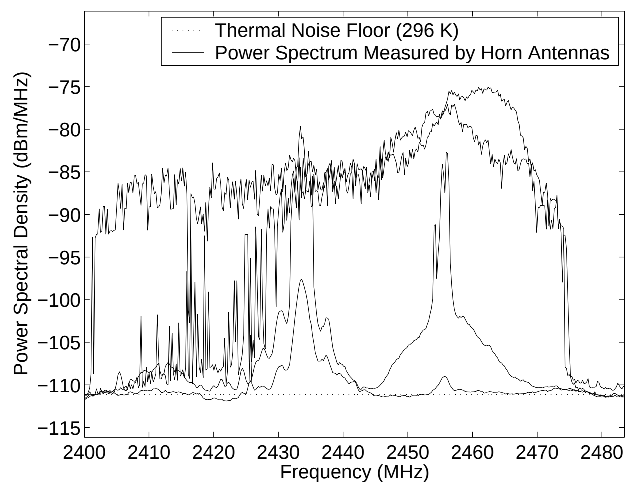

Fig 11.Spectrum measurement at rural sites in ISM 2.4GHz band

The statistical analyses are given in Table V. In all sites, the average received power was higher than -111 dBm/MHz and the standard deviations became also high indicating the existence of the man-made signals without an exception.

TABLE V
STATISTICAL ANALYSIS OF DATA IN ISM 2.4 BAND

Site	Average [dBm/MHz]			Standard Deviation [dBm/MHz]		Percentage of Man-Made Signal [%]	
	HOR	VER	50 ohm	HOR	VER	HOR	VER
Urban I	-83.1	-84.4	-111.1	-66.6	-67.5	6.08	4.50
Urban II	-92.2	-89.8	-111.3	-71.5	-70.1	4.35	3.58
Rural I	-85.1	-82.5	-111.4	-67.7	-66.6	0.62	0.78
Rural II	-97.1	-100.8	-111.3	-74.0	-76.6	2.64	3.67

The estimated percentage of the man-made signals rose as high as 6.08 % showing the severe level of penetration of the man-made signal presumably from multiple unknown sources with various types of operation (including WiFi transmitters, cordless telephones, microwave ovens, and various consumer products).

IV. Discussion

The results from each frequency band tested are quite unique as should be expected based on the varying regulations for each of the bands. The GPS L1 band is a strictly controlled and protected band. Measurement of the GPS L1 band displayed no or very rare appearances of the man-made signals at all sites. The Unified S band showed the mixed result. It is used for space science but also exposed to commercial use such as the auxiliary channel for TV broadcasting. In the rural sites, no man-made signals were detected while there were high level of man-made signals measured in the urban sites. The ISM band is the most open band and is believed to be the most heavily populated frequency band of the three tested. It is a frequency band allocated for unlicensed spectrum use and is finding increased use for unlicensed wireless technologies such as wireless networks and cordless telephone operations and also contains radio energy from microwave ovens. At all measurement sites, the band was fully occupied by the strong man-made signals. As shown in the previous section, the man-made signals dominate the natural noise floor at all sites – even Yosemite National Park.

- The 1.5 GHz GPS band is relatively pristine (quiet).
- The 2.0 GHz band has emissions due to non-Government services.
- The 2.4 GHz ISM band is discernibly noisier than the foregoing bands.

Rural areas are less populated and therefore are supposed to contain lower level of the man-made signals compared to urban areas. It was true in the GPS L1 band and the Unified S band. But the ISM 2.4 GHz was proved to be the exception as a result of the high penetration of such devices even into rural areas. Microwave ovens, cordless phones and WiFi transmitters are virtually ubiquitous and leave no place free of the man-made signals. Yet in rural area the number of those man-made signal sources is limited and the spectrum was found to be noisy in limited time or in limited direction. On the contrary urban areas had significant levels of detectable man-made noise at all times and in all directions thus reflecting the high number of the man-made signal sources in various forms. Lastly, the urban sites showed noisy RF environments but the rural sites were mostly quiet with the exception of the ISM 2.4 GHz band.

- Urban areas are noisier than rural environments.
- Airports are generally similar to urban areas and harbors are generally similar to rural areas in the GPS L1 band

Based on the results, the existing regulations have been shown to be functioning properly to support and protect the individual spectrum use as allocated. In other words, the reality of the radio spectrum reflects the applied regulation within it. In the protected band, the spectrum is kept clean of the man-made signals and thus secure and stable service is guaranteed. In the open bands, the spectrum frequently contains high levels of the man-made signals with a variety of signal structures. It also shows the highest density in terms of usage per bandwidth. However, each system experience severe competition from one another, limiting the effective range and increasing susceptibility to communication failure due to hostile environment in which it must operate.

- Regulation determines reality in radio frequency environments.
- Open spectrum allows more applications but brings limitations to their performance.
- Protected spectrum allows less applications but guarantees stability of critical systems.

V. Conclusion

Taken together, the measurement data in this study send a message – *regulation must be very sensitive to the function of the band, because the rules determine the radio environment.* Open bands, like the ISM band, do become populated with the man-made signals. This openness brings many terrestrial users and great utility, but does render the band useless for space-based applications. The Unified S band is used for critical satellite communications from a finite number of ground stations. Hence, an intermediate regime can work, because the band does not need to be quiet everywhere. The GPS band serves safety-critical applications everywhere. Hence, a most restrictive regime is needed here, and the natural noise floor should be the basis of the operation in this band. Considering the diverse objectives and the requirements of the band allocations, the spectral separation between the frequency bands and the different types of regulations as applied today are considered to be proper for the common good of the individual systems for their stable service and best utilization.

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Juyong Do is a Ph.D. candidate in Electrical Engineering at Stanford University. He received B.S. degree from Yonsei University in Korea in 1998 and M.S. degree from Stanford University in 2003 in Electrical Engineering. He worked for Motorola between 1998 and 2000 as a communication hardware engineer in a CDMA division. Major interests are Positioning technology and Wireless communication theory.

Dr. Dennis M. Akos completed the Ph.D. degree in Electrical Engineering at Ohio University within the Avionics Engineering Center. He has since served as a faculty member with Luleå Technical University, Sweden, as research staff with the GPS Laboratory at Stanford University, and is currently is academic faculty with the University of Colorado Boulder.

Dr. Per Enge is a Professor of Aeronautics and Astronautics at Stanford University. He received his B.S. in Electrical Engineering from the University of Massachusetts at Amherst in 1975, and his M.S. and Ph.D., both in Electrical Engineering, from the University of Illinois at Urbana-Champaign in 1979 and 1983. Professor Enge's research focuses on the design of navigation systems which satisfy stringent requirements with respect to accuracy, integrity (truthfulness), time availability, and continuity.