A Digital Signal Processing Based Ka Band Satellite Beacon Receiver / Radiometer

Cornelis Jan Kikkert
Electrical and Computer Engineering
James Cook University
Townsville, Australia
Keith.Kikkert@jcu.edu.au

Owen Patrick Kenny
Electrical and Computer Engineering
James Cook University
Townsville, Australia
Owen.Kenny@jcu.edu.au

Abstract—This paper describes a Ka band Satellite Beacon Receiver / Radiometer for measuring both the sky noise and the attenuation caused by rain and water vapor to satellite signals, at the same frequency and look angle. To enable the receiver to stay locked to satellite beacon signals with received power levels between -110 dBm and -170 dBm, a receiver with an ultra low phase noise, an absence of spurious signals and using advanced Digital Signal Processing (DSP) techniques is required. To obtain rain fade statistics, the received signal power of a satellite beacon is recorded continuously at an eight times per second rate.

Keywords— Satellite Beacon Receiver, Radiometer, Rain Fade, Rain Attenuation, DSP, DDC, FFT, Digital Down Conversion.

I. INTRODUCTION

As the satellite transmissions at lower frequencies become more congested, it is necessary to use higher frequency bands such as the 18 – 21 GHz, Ka, band for additional services [1]. The attenuation due to rain increases as the transmission frequency increases [2]. At a 150mm/hr rain rate, which is common in the tropics for short durations, an attenuation of 20 dB per km is observed at 21 GHz, while the same rain only causes a 5 dB per km attenuation in the 11 – 13 GHz, Ku, band. In addition, there is a water absorption peak at 22.2 GHz, so that high humidity causes additional attenuation to the received signal. It should be noted that at C band and Ku band the attenuation due to water vapor is negligible. There can be rapid variations in signal strength, called scintillation, due to variations in the refractive index in the troposphere and the ionosphere. These variations occur at rates up to 0.5 Hz, so that the beacon receiver has to have a sampling rate of at least two samples per second to accurately record these effects.

To determine the minimum receiver dish size needed for a target satellite-availability specification of a proposed commercial service, the actual rain attenuation distribution should be measured, at the location where the receiver is to be established. An accurate rain attenuation distribution can best be determined using satellite beacon receivers and radiometers. The resulting rain fade statistics can then be used to enhance the ITU propagation model for the local region.

The James Cook University - Satellite Transmission Rain Attenuation Project (JCU-STRAP) team has been building and operating Satellite Beacon Receivers for many years [3-7]. With advancements with DSP processor capabilities greater computational throughputs are achievable resulting in larger FFT sizes. In this case, a 4 k FFT was implemented as compared to the previous 1 k FFT used in the previous STRAP systems. This together with using a 12 bit instead of a 10 bit ADC results in an 18 dB increase in the system noise performance.

Previous Ku band measurements have shown rain fades in excess of 35 dB [3]. Such deep fades will occur more often at Ka band frequencies, particularly in tropical areas. A satellite beacon receiver is thus to have as large a dynamic range as possible.

II. RECEIVER DESIGN REQUIREMENTS

A. RF Specifications

For a satellite beacon receiving system, tracking antenna dishes cannot be used as they cause fluctuations in the received signal strength. The antenna dish size must be small enough so that negligible variation in received signal level occurs as the satellite moves around inside its allowed orbital allocation. The antenna dish must be big enough to result in an adequate signal to noise ratio and thus give an adequate rain fade dynamic range. For a typical 20 GHz satellite Ka band beacon receiving system, with a 1.2 m antenna looking at a +30 dBW satellite beacon, the received signals at the back of the antenna dish is approximately -110 dBm. For a typical receiving antenna temperature of 70 K and a satellite receiver with a noise figure of 4 dB and a final receiver detection bandwidth of 17 Hz, the noise power referenced to the antenna is -164 dBm. Under ideal conditions, this results in an expected Carrier to Noise (CNR) ratio of 54 dB. If a signal >6 dB above the noise can be detected, then a 48 dB rain fade can be tracked accurately.
To accommodate frequency drift due to ageing of the satellite beacon and Crystal oscillators used in the Beacon Receiver, the receiver should automatically lock onto a Satellite Beacon signal within a ±400 kHz frequency range of the Beacon frequency design value.

B. Radiometer Operation

In the tropics, raindrops are typically at a temperature of 273 K to 300 K. Each raindrop produces a small amount of thermal radiation. The higher the rain rate the deeper the rain-fade and the larger the thermal noise that is received by the beacon receiver. Radiometers are instruments that record this received noise [7]. They can be operated without a satellite beacon signal being present. It is highly desirable for a satellite beacon receiver to also record the sky noise at the same frequency and in the same direction as the satellite beacon transmission. This allows radiometer models to be improved, thus retrospectively enhancing the accuracy radiometer measurements made prior to satellite beacons being available. The JCU-STRAP beacon receiver, described in this paper measures both the beacon signal rain fade and the corresponding rise in sky noise and records them simultaneously. Conventional radiometers use a Dicke Switch to perform the comparison between the measured noise and a noise reference. The gain of this radiometer/receiver is stable enough for noise power measurements to be made using DSP techniques. An excess noise source is used to calibrate the beacon receiver gain at half hourly intervals and thus provide absolute rain fade and radiometer measurements.

C. Data Logger Specifications

The JCU-STRAP beacon receiver radiometer has a data output rate greater than eight samples per second and a signal and noise filtered bandwidth of 0.5 Hz and can thus accurately track scintillation. This data is then recorded on a PC based data logger, for later analysis. In addition meteorological data, such as rainfall, from a tipping bucket rain gauge, temperature and humidity are also recorded.

D. DSP Requirements

To obtain a 50 dB dynamic range, a final measurement bandwidth of 20 Hz or less is required. This cannot be achieved economically using analogue hardware. As a result, the beacon signal is digitized after it has been filtered, amplified and shifted to 23 MHz as shown in Fig. 1. A Digital Down Conversion IC is used to provide the final filtering for the beacon signals, using digital CRC filters. A sliding 4k FFT is performed on the resulting 70.32 kps data stream resulting in a 17.7 Hz per bin spectrum, thus satisfying the dynamic range requirements. The satellite beacon signal power and sky noise power are determined from this spectrum. The signal power and noise power values are filtered with a 2Hz bandwidth and decimated to provide an 8.5 sample per second output data rate, which is fast enough to allow scintillation to be investigated.

III. RF Design

Two JCU-STRAP satellite beacon receivers, as outlined in this paper were built. One system is in operation at the Communication Research Centre (CRC) in Ottawa, Canada, to receive the 20.199 GHz Ka band beacon on the Anik F2 satellite. The other receiver at NTU in Singapore, is designed to receive either the 20.199798 GHz Ka band beacon on the Ipstar [9] satellite or the 18.9 GHz Ka band beacon on the WINDS [10] satellite. Fig. 1 shows the block diagram of the beacon receiver, using the Anik F2 and Ipstar frequencies as an example. It consists of a satellite dish and Ka Band Low Noise Block converter (LNB), which shifts the 20.199 GHz signal to 949 MHz.

Figure 1. Block diagram of the beacon receiver.

This signal is then transmitted to the indoor unit, which houses the remaining blocks shown in Fig. 1. The indoor unit takes the 949 MHz UHF signal and detects the satellite beacon signal and determines the sky noise and sends both these results to the data logger using an RS232 port on the beacon receiver. The top unit in Fig. 2 shows the indoor unit of this Ka band receiver installed at NTU in Singapore, the bottom unit is a JCU-STRAP Ku band satellite beacon receiver of an earlier design [3-7].
The outdoor unit, as shown in Fig. 3, is mounted at the satellite dish and contains regulated power supplies to ensure that the DC supply voltages to the LNB and the excess noise source do not contain any mains frequency related components. The control circuitry in the outdoor unit allows the DSP to switch the excess noise source ON for calibration of the receiver gain. A commercial Ka band LNB (NORSAT 9000HB) [11], which has a noise figure of less than 1.6 dB, a conversion gain of more than 50 dB and a phase noise of less than -65 dBc at 1 kHz is used for the LNB. The actual close-in phase noise is better than those specifications.

The satellite beacon signal at the output of the dish is typically -110 dBm and the signal at the RF input of the indoor unit is typically -60 dBm. The beacon receiver should have a dynamic range greater than 50 dB, so that the smallest valid beacon signal at the RF input to the Indoor Unit is -110 dBm. In the Indoor Unit, any spurious signals created by harmonics or intermodulation distortion components of Local Oscillator (LO) signals should thus be much less than -110 dBm. To eliminate Intermodulation (IM) products due to different LO frequencies, one local oscillator is used and all the other LO frequencies are harmonically related.

The phase noise of any local oscillators used in the beacon receiver will add to the phase noise of the received satellite signal. As a result, the phase noise of any local oscillators used in the beacon receiver should be as small as possible. To achieve this, a 54 MHz crystal oscillator is used for the basic LO and all the other LO frequencies are obtained by harmonic frequency multiplication. The 162 MHz VHF LO is the third harmonic of the crystal oscillator, obtained by using a helical filter to filter out the required 162 MHz signal. The 810 MHz UHF LO is the fifth harmonic of 162 MHz and is produced using a microstrip filter and Microwave Monolithic IC’s (MMIC). This results in a very low phase noise for all local oscillators, but requires each beacon receiver different LO and IF frequencies, increasing the cost of the hardware.

These local oscillators are then used in the UHF and VHF IF strips to amplify and frequency shift the satellite beacon signal to 23 MHz. This 23 MHz signal is filtered using a specially designed LC filter, with a 1 MHz bandwidth. The phase noise at the 23 MHz IF due to the local oscillators in the indoor unit is less than the phase noise of the Anik F2 satellite beacon or the LO used in the NORSAT Ka band LNB.

The 23 MHz VHF IF output signal is digitized using a 12 bit ADC. Since the 23 MHz IF signal has a 1 MHz bandwidth, subsampling with a frequency of 18 MHz, being one third of the 54 MHz crystal oscillator frequency is used. This then results in an effective 5 MHz IF for the digitised signal. An Analog Devices AD6620 Digital Down Conversion (DDC) IC is then used to shift this digitised signal to close to zero frequency with in-phase (I) and quadrature (Q) components. The functional block diagram of this IC is shown in Fig 4.
IV. DSP HARDWARE

As shown in Figs. 5 and 6, the digital hardware for the beacon receiver system consists of a DSP processor, a Complex Programmable Logic Device (CPLD), an AD6600 high bandwidth analogue-to-digital converter (ADC), an AD6620 DDC, a front panel LCD display, an RS232 communication port, a digital-to-analogue converter and internal and external memories.

The ADSP 21369 SHARC [12] is a 2.4GFlop DSP processor and has sufficient high-bandwidth I/O ports and direct memory access (DMA) for external RAM to perform all the DSP processing tasks required for this beacon receiver. To minimize the cost for the very small production runs of the beacon receiver, a commercial development board is used [13]. This board also contains RS232 UARTs and audio CODECs, which are used to provide both the digital and analogue data outputs shown in Fig. 5. The development board also contains Flash Memory and RAM to allow the DSP to boot as an independent unit.

The parallel expansion port on the DSP development board is used to connect external devices via the CPLD to ensure correct communication to external devices, which are accessed as memory mapped locations [14].

The DDC internal control registers are accessed through the microcontroller interface port of the DDC. The I/Q data from the DDC is passed to the DSP for processing via the serial port of the DDC.

A. System Initialization

When the system is turned on, the DSP initializes its internal configurations and external hardware including the DDC, LCD and memories. The DDC takes the 18 Msps digitized satellite beacon signal and filters and decimates it to 70.3125 kps data rate with a ±35.156 kHz bandwidth, centered at zero frequency with in-phase (I) and quadrature (Q) components. The AD6620 DDC IC performs the digital down conversion in three stages. The first stage consists of a second order CIC decimation filter, the second a 5th order CIC decimation filter, and the final stage is a hardware 256 tap FIR filter. The resulting DDC output is a serial 24-bit I/Q data stream.

To ensure that the decimated data is correct the DSP verifies that all the DDC settings are correct, and if so a message is displayed on the front panel indicating that the DDC has been programmed correctly, otherwise the faulty data is resend and re-verified. If the DDC settings are still incorrect, an error message is displayed.

A Numerically Controlled Oscillator (NCO) controls the frequency shifting to ensure that the satellite beacon signal is shifted to near zero frequency.

Once the external and internal devices have been initialized, the system starts to evaluate the signal power and noise power in the search mode in order to locate the satellite beacon.

B. Signal and Noise Power Estimation

The basic requirement of the Satellite Beacon Receiver is to estimate the received signal power and sky noise power as these vary due to different environmental conditions. These power estimates are determined by observing a section of the spectrum, $Y_0(f)$, around the frequency location of the beacon signal as described by:

$$Y_0(f) = [S(f - f_0) + N(f - f_0)]W(f)$$  \hspace{1cm} (1)

Where $f_0$ is the frequency location of the beacon signal, $S(f)$ the signal spectrum, $N(f)$ the noise spectrum and $W(f)$ the spectral window function.

The process described by (1) is implemented using the DDC by setting the NCO frequency to the appropriate offset frequency $f_0$. At a discrete instance of time, $l$, the down converted signal is weighted by a Blackman-Harris window and a decimation-in-frequency 4 k FFT is calculated by the DSP as described by:

$$Y_0(l,k) = [S(l,k - k_{NCO}) + N(l,k - k_{NCO})]W_{DDC}(k)$$ \hspace{1cm} (2)

Where $k_{NCO} = f_{NCO} \times N/F_s$, $f_{NCO}$ denotes the frequency of the NCO, $W_{DDC}(f)$ denotes the spectral window function and $N$ is the size of the FFT, being 4096 in this application.
The FFT is used to obtain an estimate of the power spectral density estimate (PSD) by a recursive averaging process described as:

\[
\hat{P}_s(k) = a|Y_B(l,k)|^2 + b\hat{P}_{s-1}(k) = W_B(k-k_o) + \hat{P}_{N_l}(k) \quad (3)
\]

The variables, \(a\) and \(b\) in (3) are adaptive coefficients, which are changed depending on the signal-to-noise ratio estimate. The resulting PSD estimates contain the power spectrum of the windowed signal, \(W_B(k-k_o)\), and the noise power estimate, \(\hat{P}_{N_l}(k)\).

The noise power estimate is determined by averaging the PSD on both sides of the signal peak as indicated by:

\[
\hat{P}_{N_l} = \frac{1}{N - 2N_s - 2G} \left[ \sum_{k=N_s}^{k+N_s} \hat{P}_s(k) + \sum_{k=-N_s}^{-k_s} \hat{P}_s(k) \right] \quad (4)
\]

The number of bins over which the averaging is performed is \(N = 2N_s + 2G\) where \(N\) is the size of the spectrum, in this case 4 k. To ensure that the ±25 kHz flat portion of the spectrum, as shown in Fig. 10, is used in the calculations, \(N_s\) bins at the edge of the spectrum are excluded from these power calculations. To ensure that the noise power estimate does not include any signal components a guard band, \(G\), is set around the spectral signal component, as illustrated in Fig. 7.

\[
SNR = 10\log_{10}\frac{\hat{P}_s - 10\hat{P}_{N_l}}{10} \quad (8)
\]

A deep rain fade is present if the maximum SNR is less than 20 dB so a second search is initiated with the coefficients, \(a\) and \(b\) in (3) adjusted so that \(a = 0.1\) and \(b = 0.9\). This results in a smooth estimate of the noise PSD, thus preventing the system from locking onto any spurious noise spikes. If the maximum SNR is greater than 10 dB then the corresponding frequency band is chosen as containing the beacon signal. If the maximum SNR is still less than 10 dB then the system is set to radiometer mode and the NCO frequency is set to 23 MHz. In this mode, only the sky noise is evaluated, so the receiver is then used as a conventional radiometer, as discussed in Section VI of this paper.

Figure 7. Signal and Noise measurement regions.
In order to shift the beacon signal to the near zero frequency location, $f_o$, the frequency bin location of the beacon signal within the band is determined by finding the peak location as indicated by:

$$k_o = \max_k(\hat{P}_i(k))$$  \hspace{1cm} (9)

The NCO is adjusted to the required frequency:

$$f_{NCO} = f_{NCO}' + f_o - f_p$$  \hspace{1cm} (10)

Where $f_{NCO}'$ is the corresponding NCO frequency search band; $f_o = k_o*(F_s/N)$ corresponding to the frequency of the beacon signal within the frequency search band; and $f_p$ corresponds to the frequency where the signal is parked within the observation frequency band.

After the beacon signal has been located and appropriately positioned, the system enters into the normal operational mode.

**D. Normal Operational Mode**

In the normal operational mode the beacon signal level and the sky noise power are accurately determined using equations (3) to (6) and setting the recursive averaging filter coefficients $a$ and $b$ in (3). The DSP performs a 4 k FFT on the I/Q data every 1024 new samples, thus 68.66 FFTs are performed each second.

With each successive power spectrum calculation, the beacon signal frequency is also determined. Since the LNB can have a diurnal drift of ± 70 kHz, the downconverted beacon signal frequency is obtained for each FFT. If the beacon signal frequency is further than a preset limit from the desired beacon frequency, the NCO in the DDC is adjusted under DSP control to ensure that the satellite beacon remains at -1.7 kHz ± 850 Hz at the output of the DDC.

When the SNR is greater than 20 dB, the coefficients, $a$ and $b$ in (3) are set such that no averaging takes place. If the SNR is between 20 and 10 dB, the coefficients are varied, depending on the SNR value to provide progressively more averaging as the SNR decreases. When the SNR is less than 10 dB, the coefficients are set to provide the maximum amount of averaging. This averaging smooths the noise floor and makes it easier to detect a satellite beacon signal during deep rain fades or during the search routine when the receiver is acquiring a low level signal. As a result, the receiver can reliably acquire and lock onto signals that are just 5 dB above the noise and accurately detect signals just 3 dB above the noise.

The satellite beacon signal and sky noise estimates are filtered using specially designed 8th order IIR filters with a 0.5 Hz cut off frequency to enable scintillation to be investigated accurately. These filters exhibit a very fast settling time, low overshoot and a good attenuation to out of band signals. The signal power and sky noise power are displayed on the front panel, as shown in Fig 9, as well as being sent to the data logger using an RS232 interface on the DSP board. In addition, the NCO frequency and error messages are also sent to the data logger.

![Figure 8.](image)

**Figure 8.** NCO Adjustment shifting the beacon signal to desired position near zero frequency.

![Figure 9.](image)

**Figure 9.** LCD Display in Operation Mode

The SNR is also filtered to give a very-long-term average, corresponding to the clear sky signal and noise conditions. If the SNR level is 3 dB less than its very-long-term average, indicating that a rain fade is in progress, the calibration noise source is turned off to ensure that no useful data is lost.

When the SNR level is 20 dB less than its very-long-term average, indicating a deep rain fade, a fade timer is started and the receiver will keep the same NCO frequency, even if no signal is detected. The receiver is very stable and when the rain fade reduces, the satellite beacon will still be within the frequency range covered by the FFT. Consequently, the receiver will regain lock immediately after the signal is slightly above the noise level. Long deep fades can thus be accurately tracked.

To ensure that the beacon receiver does not permanently lock onto the wrong frequency, the receiver starts a new search if the SNR is less than 10 dB for more than 20 minutes, if no signal is found during that frequency sweep, the receiver will switch to radiometer mode.

The excess noise source is turned on for 15 seconds once every half hour. The resulting noise level recorded by the data logger provides an accurate measure of the complete receiver gain, including the gain of the LNB. This is then used for rain fade and sky noise calibration.
during data analysis. To provide data with a traceable accuracy, the results from this noise calibration is not used to change any receiver or DSP gains.

V. RADIOMETRIC MODE

The receiver in normal operating mode determines both the beacon signal power and the sky noise power. In the absence of a beacon signal, the receiver can still accurately determine the sky noise and thus operate as a Radiometer. If no signal power is detected, the receiver automatically switches to Radiometer mode. In this mode the NCO is fixed and set to the designed operating frequency (23 MHz for this receiver) and the IIR averaging filtering coefficients of (3) are set to give the maximum filtering.

In the earlier JCU-STRAP receiver/radiometer [5] this noise power measurement was simply recorded. A clear sky reading had to be taken as the reference for the sky noise power. The gain of the LNB, which is exposed to the outside temperature, will vary on a daily basis, some gain variations of the indoor unit may also occur with temperature.

In this receiver, to make both the beacon receiver and the radiometer measurements more accurate, a Ka band excess noise source is added in between the horn of the satellite dish and the LNB. This noise source is coupled into the LNB input using a waveguide coupler. The noise source is normally turned on for 15 seconds once every half hour under DSP control. The noise figure due to the insertion of the waveguide and the excess noise source 50 Ω termination thermal noise coupling into the LNB, is less than 0.9 dB and is less than the noise figure of a typical coaxial switch. The total noise figure of the JCU-STRAP receiver is thus less than 4 dB, with the noise source included and the noise source off.

The output of the LCD display under Radiometer mode is shown in Fig. 10.

VI. RESULTS

Fig. 11 shows the output spectra produced by the DSP. The bottom (blue) curve is the spectrum when a signal generator is used as an input to the ADC. The middle (cyan) curve shows the spectrum for the same input signal but with noise added such that a similar signal to noise ratio is obtained as is received from the Anik F2 satellite. The top (red) curve shows the same input signal with noise added such that a similar signal to noise ratio is obtained as is received from the Anik F2 satellite, whilst the excess noise source in ON. By comparing Fig. 11 with Figs. 3 and 5 of reference [7] describing a PLL based beacon receiver, it can be seen that a significantly lower phase noise is obtained in this JCU-STRAP receiver. Some low level unwanted components due to radiation from the DSP can be seen at 7 kHz above the carrier. This is however, 15 dB below the noise level received from the satellite and will not degrade the performance.

The actual measured clear sky signal to noise ratio at CRC in Ottawa using the Anik satellite is 40 dB with the noise source ON and 53 dB with the noise source OFF. These figures are close to what is expected. At NTU in Singapore, using the Ipstar satellite the measured clear sky signal to noise ratio is 37 dB with the noise source OFF. The beacon receiver will still locked with a signal that is just 3 dB above the noise, thus giving a track-able fade depth of more than 50 dB for CRC and 34 dB for NTU. This demonstrates the benefits of using the techniques described in this paper.

![Figure 11. Spectrum of a test signal after digital demodulation.](image)

A deep rain fade obtained at NTU with the JCU-STRAP receiver is shown in Fig. 12. The clear-sky signal level is 0 dB. As seen from Fig. 12, the signal power drops 30 dB at the receiver, as the rain fade finishes, the
receiver regains lock immediately the signal is slightly above the noise level. This illustrates that long deep fades can thus be accurately tracked with this system.

The excess noise source is turned on by the DSP for 15 seconds once every half hour as shown in Fig. 12 at the 83 minute time. The resulting noise level recorded by the data logger provides an accurate measure of the complete receiver gain, including the gain of the LNB. This is then used for rain fade and sky noise calibration during data analysis. The noise source is not turned on during a rain fade, thus ensuring that no useful data is lost.

Fig. 13 shows a deep rain fade at CRC in Canada. Comparing Fig. 12 and 13 shows that the signal strength received from the ANIK satellite beacon at CRC, is larger than the signal strength received from the IPSTAR satellite in Singapore.

VII. CONCLUSION

The new JCU-STRAP satellite beacon receiver described here uses ultra low phase noise oscillators and advanced DSP technology to obtain a larger dynamic range than was previously possible. A 53 dB SNR is obtained in practice. Using an excess noise source at half hourly intervals to obtain accurate gain calibrations of the receiver, increases the rain fade accuracy and allows the receiver to be used as an accurate radiometer. The use of advanced DSP technology enables the receiver to have a dynamic range which is purely determined by the beacon signal and sky noise. The final data rate of more than eight samples per second allows scintillation to be observed.

ACKNOWLEDGEMENT

The authors thank the CRC in Ottawa, Canada and NTU in Singapore for providing the funding to permit these beacon receivers to be constructed and the data for Fig 12 and 13. The authors thank James Cook University and in particular, the staff of the School of Engineering for their support and encouragement in particular Mr. Geoffrey Reid who wrote the code for the data logger and Mr. John Renehan and Mr. Lloyd Baker who assisted with the construction of the JCU-STRAP system described in this paper.

REFERENCES