# A SURVEY OF SOFTWARE-DEFINED RADIO TECHNOLOGY FOR AERONAUTICAL MOBILE TELEMETRY

Joshua Gillis and Travis Berry
Department of Electrical & Computer Engineering
Brigham Young University
jgill333@student.byu.edu, tberry9@student.byu.edu

Faculty Advisor:
Michael Rice

## ABSTRACT

This paper surveys the capabilities of commercially available software defined radios (SDR) and their suitability for use as receivers and demodulators in aeronautical mobile telemetry (AMT). A case study, defined by 10 Mbit/s SOQPSK-TG operating in any of the IRIG 106 frequency bands, was used to determine SDR suitability for AMT. The survey investigated the frequency range, sample rate, the number of RF input ports, noise figure, automatic gain control (AGC), and cost. Different configurations are examined based on the SDRs capabilities and their use. The results show the costs of the SDRs along with their capabilities. Non-SDR options—digitizing tuners and data acquisition cards—are also briefly surveyed to consider options in which they may be used instead of an SDR.

## INTRODUCTION

Aeronautical mobile telemetry (AMT) is the one-way downlink sending onboard data from an airborne test article (TA) to a ground station. There are two important reasons as to why AMT is used in test flights. The first is to protect the safety of test pilots (in the case of manned flight) and people and property on the ground. The second is to receive on-board measurements that can be analyzed to make improvements to the TA.

The typical telemetry ground station contains many different components. An SDR can be used as the receiver/demodulator component in the ground station. However, not all SDRs are equipped to handle AMT requirements. In this paper, we provide an analysis of commercially available SDRs capable of supporting AMT.

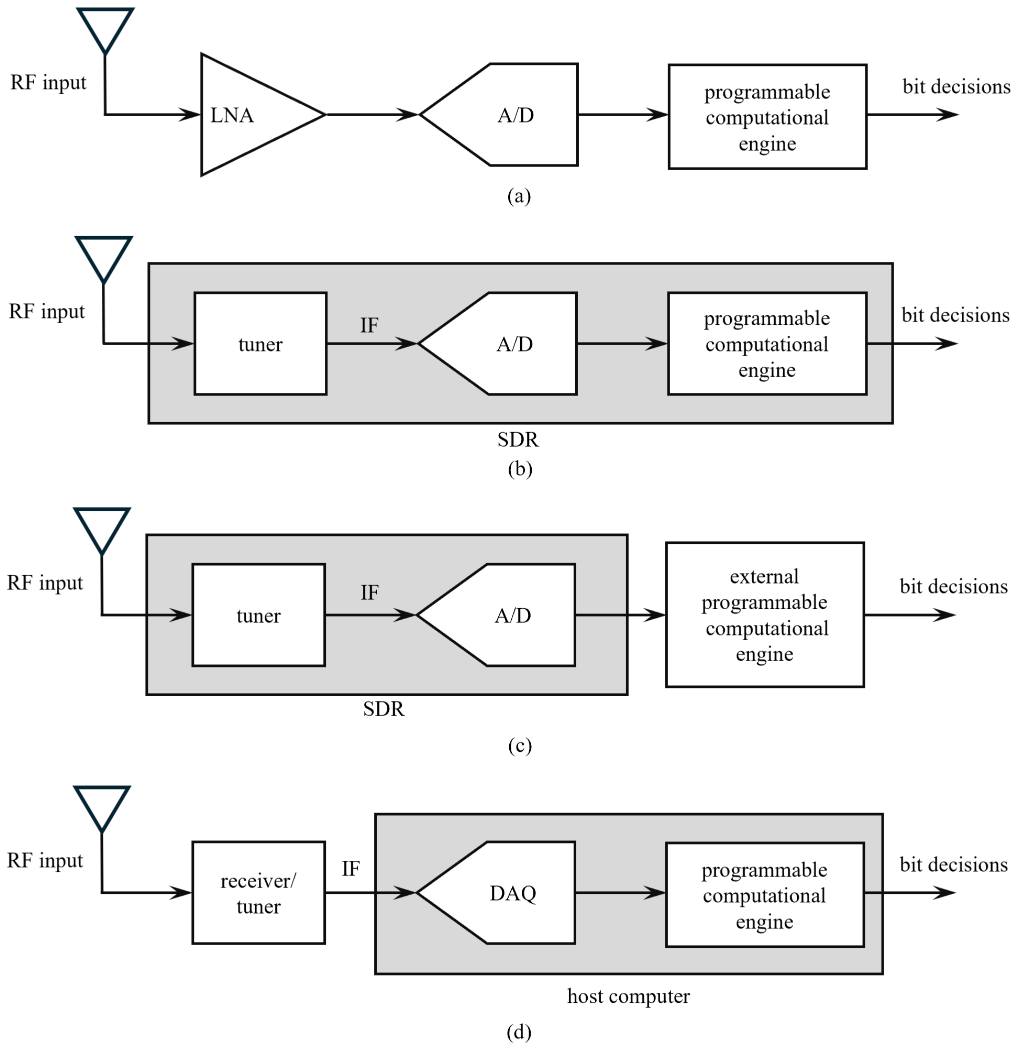


Figure 1: Architectures for sampled data telemetry receivers: (a) the ideal SDR architecture; (b) the current state of the art with an internal programmable computational engine; (c) the current state of the art with an external programmable computational engine; (d) a common legacy approach using a receiver/tuner and a data acquisition card connected to a programmable computational engine.

## SOFTWARE DEFINED RADIO

Software-defined radios are not new to aeronautical mobile telemetry and have been widely studied. In the AMT context, SDRs have been investigated as receivers [1, 2, 3, 4], transceivers [5, 6], and digital processors [7, 8]. The versatility of an SDR gives it an advantage in practical and academic settings.

The ideal software defined radio is illustrated by the block diagram in Figure 1 (a) [9, 10]. The ideal SDR is little more than an antenna, an A/D converter, and a programmable computational engine. The programmable computational engine performs tuning, channelization, resampling, demodulation, etc. to produce bit decisions. When the SDR concept was first published, the A/D converter was the bottleneck [11]. Advances in A/D converter technology over the past 25 years have made it possible to sample over a GHz of contiguous RF spectrum. Consequently, the SDR bottleneck is now the data path bandwidth of the programmable computational engine [12].

To address A/D converter limitations (in part) and data path bandwidth limitations, the architecture shown in Figure 1 (b) has emerged. The tuner performs channelization and RF to IF conversion using analog components. The IF may be either one of the standard microwave bandpass IF frequencies such as 70 MHz or it may be zero, in this case the IF comrises I/Q baseband signals. This reduces the sample rate requirement for the A/D converter, which in turn reduces the data path bandwidth requirement for the programmable computational engine. The programmable computational engine is a combination of FPGAs and programmable processors.

Some SDRs have limited internal computational capabilities. In this case, an external programmable computational engine is used to process the IF samples. This architecture is shown in Figure 1 (c). The external programmable computational engine may include FPGAs and programmable processors, including graphics processing units GPUs.

FPGAs can usually perform more computations per unit time than a programmable processor, but are generally more difficult to program. Because of this, the internal programmable computational engine–typically an FPGA–may be bypassed for ease of programming despite the FPGAs higher processing speed.

When the internal programmable computational resources of the SDR arrangement shown in Figure 1 (c) are bypassed, the SDR is little more than a software configurable tuner and IF sampler. When the SDR has no internal programmable computational resources, the system is often called a *digitizing tuner*. Digitizing tuners perform channelization and down conversion to IF. Usually the IF is I/Q baseband.

The connection between the SDR and the external computational engine varies from low-rate USB to 100G Ethernet. In the authors' experience, the bandwidth of the SDR output is often the bottleneck when using an external programmable computational engine.

Figure 1 (d) illustrates the arrangement where RF tuning and IF conversion are performed by an external (usually analog) receiver. In this case the IF is usually one of the standard microwave IF frequencies such as 70 MHz. IF sampling is performed by a data acquisition (DAQ) unit, commonly in the form of a card inserted into a PCI-express slot or a VME chassis. In this arrangement, the host computer houses both the DAQ and the programmable computational engine.

Strictly speaking, the architectures shown in Figures 1 (a) - (c) are SDRs. For the case where the SDR in Figure 1 (c) does not contain any programmable computational resources, usage of the term "SDR" to describe it is not consistent. The survey results presented below include entries for all four architectures shown in Figure 1.

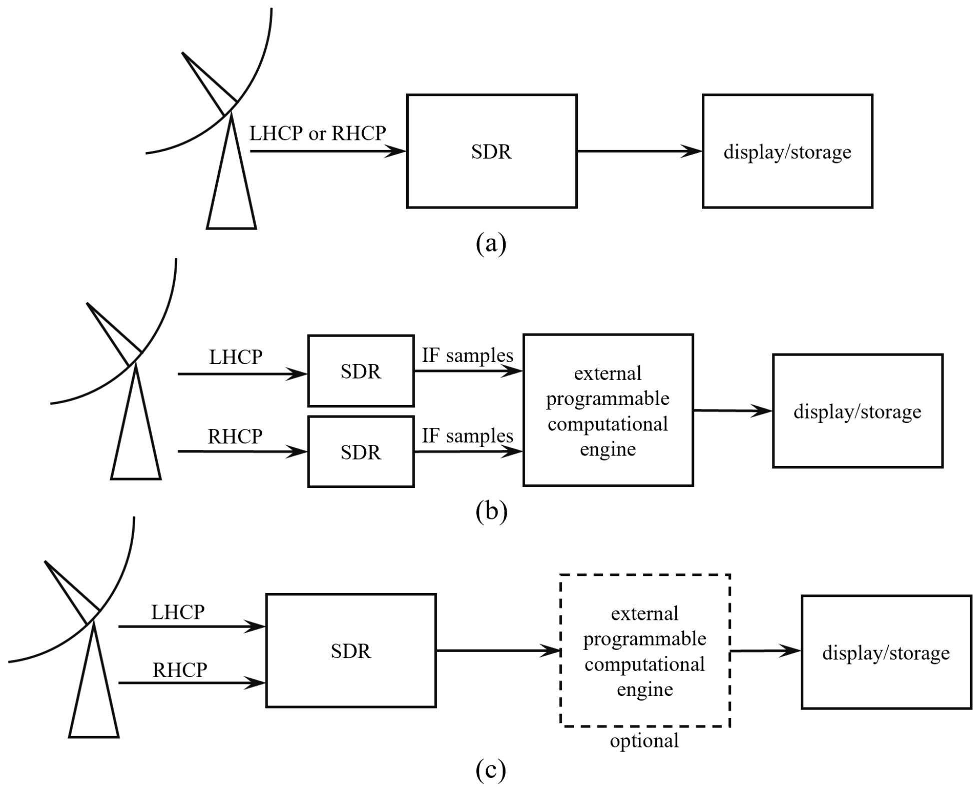


Figure 2: Architectures for diversity combining: (a) The SDR operates on only the LHCP or RHCP feed without any diversity combining, (b) two different SDRs operate individually on the LHCP and RHCP feeds, diveristy combining is performed in an external programmable computational engine; (c) a single SDR with multiple RX ports operates on the LHCP and RHCP feeds, diversity combining is performed using either the internal computational resources or an external programmable computational engine.

## CASE STUDY

The case study used for this paper is the same one used in [13]. The telemetry link is 10 Mbits/s SOQPSK-TG and the required sample rate is 20 Msamples/s [14]. If the SDR has only one RF input port, then diversity reception is not possible using a single SDR. The architecture for this case is shown in Figure 2 (a).

If diversity combining is required using an SDR with one RF input port, then two SDRs must be used, as shown in Figure 2 (b). Because diversity combining operates on samples from both RF inputs, an external programmable computational engine must be used, cf., Figure 1 (a).

On the other hand, only one SDR is required if the SDR has two or more RF inputs. The arrangement is shown in Figure 2 (c). If the internal computational resources are adequate, then diversity combining, synchronization, and detection can all be performed inside the SDR. If the internal computational resources are not adequate for all the tasks, then the next most desirable alternative is to perform diversity combining internally and the remaining tasks in the external programmable computational engine. The least desirable approach is to perform all the tasks in

Table 1: Frequency Bands for AMT [15].

| Name | Lower End | Upper End |
|---|---|---|
| Lower L-Band | 1435 MHz | 1535 MHz |
| Lower S-Band | 2200 MHz | 2300 MHz |
| Upper S-Band | 2310 MHz | 2395 MHz |
| Lower C-Band | 4400 MHz | 4940 MHz |
| Middle C-Band | 5091 MHz | 5150 MHz |
| Upper C-Band | 5925 MHz | 6700 MHz |

the external programmable computational engine because it requires the maximum data transfer bandwidth between the SDR and the external computational engine.

We surveyed commercially available SDRs and considered whether these SDRs would be suitable for aeronautical mobile telemetry. The first criterion was operation in the telemetry bands defined in IRIG 106 [15]. The IRIG 106 telemetry bands are summarized in in Table 1. The second criterion is the sample rate ($\geq 20$ Msamples/s).

Other radios, such as digitizing tuners as shown in Figure 1 (c), and receiver/DAQ units as shown in Figure 1 (d) can also be used. Radios that fit this description can be found in Tables 4 and 5.

## THE SURVEY

The survey investigated over 50 software-defined radios from several different companies and manufacturers. There is a wide range of products available, from small tools for amateur use, to large and powerful instruments for large-scale commercial and military applications. The majority of SDRs either did not meet the requirements for our case study described in the previous section, or are no longer commercially available. Table 2 lists the SDRs that met the selection criteria defined by our case study. The other commercially available SDRs are listed in Table 3.

A graphical representation of the data in Table 2 is shown in Figure 3. It is a capability vs. cost scatter plot, where capability is quantified by the product of the sample rate and the number of RF input ports. Costs ranged from $400 - $280,350 with a mean of $40,205 and median price of $12,191. Below the price range of $25,00, it is difficult to determine a pattern of cost based on the capability that we have defined. There are many other factors involved in this cost, such as its transmit capability, data interface, etc. After $25,000, the plot shows that cost increases roughly proportional to capability.

The graph does not include all aspects of the radio that affect its price. We included SDR specifications that most highly affect their performance in AMT reception to determine the capability axis. Frequency range was not included due to all the radios being capable of tuning to the IRIG 106 telemetry bands. Other capabilities, such as RF transmit capability, AGC, and NF were not considered in the plot.

Table 2: SDRs with capabilities that satisfy the case study requirements. NF is noise figure. A “Y” in the AGC column means the SDR has AGC capability; a “U” means AGC capability is unknown. Costs are in USD.

| Radio | Frequency Range | Sample Rate (Msamples/s) | # of RX Ports | NF (dB) | AGC | Cost | Reference |
|---|---|---|---|---|---|---|---|
| HackRF One | 1 MHz - 6GHz | 20 | 1 | 11 | U | $400 | [16] |
| bladeRF 2.0 micro | 47 MHz - 6 GHz | 61.44 | 2 | 7.4-12.5[a] | Y | $540 | [17] |
| USRP B200 | 70 MHz – 6 GHz | 61.44 | 1 | 8 | Y | $1,326 | [18] |
| USRP B205mini-i | 70MHz - 6GHz | 61.44 | 1 | 8 | Y | $1,387 | [19] |
| USRP N200 | DC - 6GHz | 100 | 2 | 5 | Y | $3,048 | [20] |
| SPECTRAN V6 150-6 | 9kHz - 6 GHz | 500 | 1 | 4 | U | $3,750 | [21] |
| USRP N300 | 10 MHz - 6 GHz | 200 | 2 | 5.5-6.5[b] | U | $11,550 | [22] |
| SPECTRAN V6 150-18 | 9kHz - 18 Ghz | 500 | 1 | 4 | U | $11,786 | [23] |
| R5550 | 9 kHz - 27 GHz | 125 | 1 | 12-18[c] | U | $12,595 | [24] |
| Crimson TNG | DC - 6 GHz | 325 | 4 | 3.1-7[d] | U | $15,500 | [25] |
| Signal Shark 3310 | 8 kHz - 8 GHz | 25.6 | 1 | 14-22 | Y | $22,000 | [26] |
| USRP N320 | 3 MHz - 6 GHz | 250 | 2 | 11 | U | $22,758 | [27] |
| USRP N410 | 1 MHz - 7.2 GHz | 500 | 4 | 8 | U | $29,938 | [28] |
| SPECTRAN V6 ENTERPRISE 2000EA-6 | 10 MHz – 8 GHz | 2000 | 4 | unavailable | U | $30,000 | [29] |
| CyanMid | DC - 18 GHz | 3000 | 8 | 3.1-7[d] | U | $196,350 | [30] |
| CyanPro | DC - 18 GHz | 3000 | Up to 16 | 3.1-7[d] | U | $280,350 | [30] |

[a]The noise figures are 7.4 dB (L band), 9.0 dB (S band), and 12.5 dB (C band).
[b]The noise figures are 5.8 dB (L band), 6.5 dB (S band), and 5.5 dB (C band).
[c]The noise figures are 18 dB (L band), 21 dB (S-band), and 12 dB (C band).
[d]Only the range was given; NFs as a function of frequency bands was unavailable.

Table 3: Other commercially available SDRs. A "Y" in the AGC column means the SDR has AGC capability; an "N" means the SDR does not have AGC capability; a "U" means AGC capability is unknown. Costs are in USD.

| Radio | Frequency Range | Sample Rate (Msamples/s) | # of RX Ports | AGC | Cost | Reference |
|---|---|---|---|---|---|---|
| RTL SDR v 3 | 500 kHz – 1.766 GHz | 2.4 | 1 | Y | $34 | [31] |
| RadioBerry V2 | DC - 38.4 MHz | 76.8 | 1 | Y | $155 | [32] |
| FUNcube Dongle | 64 MHz – 1.7 GHz | 0.096 | 1 | Y | $160 | [33] |
| ADALM-PLUTO | 325 MHz to 3.8 GHz | 61.44 | 1 | Y | $148 | [34] |
| Airspy RC | 24 MHz – 1.7 GHz | 10 | 1 | Y | $169 | [35] |
| Presicison Wave XtRX | 8.2 GHz - 9.6 GHz | 250 | 2 | U | $199 | [36] |
| Hermes-Lite2 | DC - 38.4 MHz | 80 | 4 | N | $269 | [37] |
| Lime SDR | 30 MHz - 3.8 GHz | 61.44 | 3 | Y | $315 | [38] |
| ELAD FDM-S2 | 9 kHz - 160MHz | 122.88 | 1 | Y | $460 | [39] |
| Xiegu G90 | 500kHz - 30 MHz | 0.048 | 1 | Y | $539 | [40] |
| SDRLab 122-16 | 300 kHz - 60 MHz | 122.88 | 2 | U | $708 | [41] |
| WinRadio WR-G31DCC 'EXCALIBUR' | 9kHz - 50 MHz | 100 | 1 | Y | $1,091 | [42] |
| ELAD FDM-DUO | 10 kHz – 54 MHz | 122.88 | 1 | Y | $1,095 | [43] |
| NetSDR | 10kHz - 32 MHz | 80 | 1 | U | $1,450 | [44] |
| SunSDR2 Pro | 10 kHz - 160 MHz | 160 | 1 | Y | $1,599 | [45] |
| FLEX-6400 | 30 kHz - 54 MHz | 122.88 | 1 | Y | $2,299 | [46] |
| MB1 | 10 kHz – 160 MHz | 160 | 4 | Y | $6,895 | [47] |

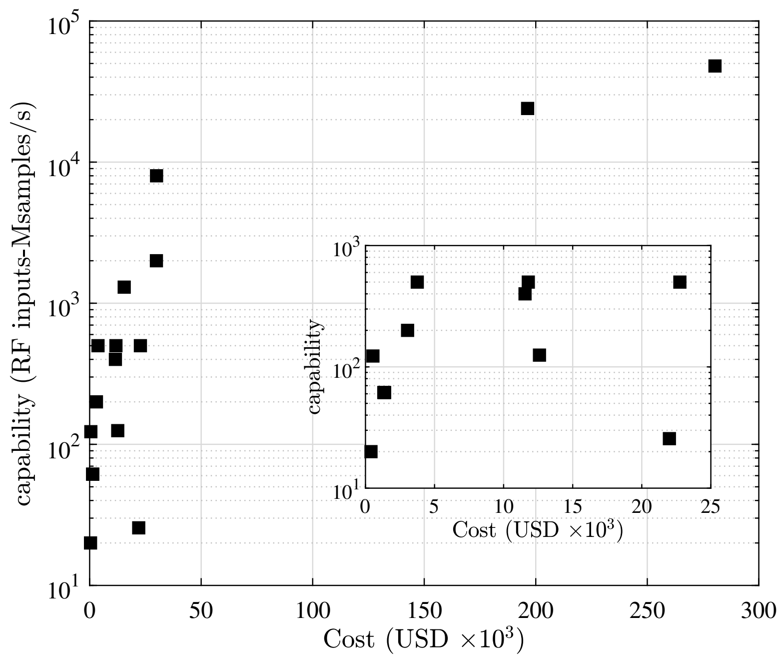


Figure 3: A graphical representation of the data listed in Table 2: capability vs. the cost. Capability is the product of the number of RF input ports and the maximum sample rate.

The noise figures (NFs) listed in Table 2 display an interesting characteristic. The NFs for the current generation of telemetry receivers range from 3 to 8 dB [1]. Nine of the SDRs listed in Table 2 have NFs in this range. Notable exceptions are the R5550 (NF is 12-18 dB) and the Signal Shark 3310 (NF is 14-22 dB). The R5550 has a remarkably large tuning range. Tuning ranges this large are often accompanied by a high NF. For example, the SMR-7522-04 digitizing tuner examined in [1] had a tuning range 800 MHz – 26.5 GHz and an NF 20-24 dB.

A big concern is the number of SDRs that do not specify an automatic gain control (AGC) capability. AGC is important in the AMT application because a test article can be very close to the receiver (a few hundred meters) or very far from the receiver (150 km). If the SDR front end gain is fixed at a high value, then the received signal saturates the A/D converter when the test article is close. Alternatively, if the SDR front end gain is fixed at a low value (to avoid A/D converter saturation when the test article is near) then the sampled data stream is limited by quantization noise when the test article is far away.

An analog AGC capability (usually implemented at analog IF) serves to scale the A/D converter input for near optimum A/D converter performance. Only five of the sixteen SDRs in Table 2 make explicit an AGC capability. One assumes that if AGC is neither mentioned nor documented, then the SDR is not equipped with the capability. Although, due to the regularity of AGC in Table 3 it is possible that more of the SDRs in Table 2 have AGC capabilities. The absence of AGC capability can be a limiting factor in the AMT application.

The survey of non-SDR radios and data-acquisition cards, in Tables 4 and 5, are not an exhaustive list of all available products. These tables are provided to give a quick scope of comparative options

Table 4: SDR alternatives: digitizing tuners.

| Radio | Frequency Range | Sample Rate | # of RX Ports | Cost | Reference |
|---|---|---|---|---|---|
| M9703A | DC to 2 GHz | 3.2 Gsamples/s | 8 | $15,698 | [48] |
| SMR 7522 | 0.8 to 26.5 GHz | 125 Msamples/s | 1 | $56,200 | [49] |
| iWR-6500 | 0.5 to 26.5 GHz | 8 Gigabits | 1 | $102,500 | [50] |

Table 5: SDR alternatives: data acquisition cards.

| DAQ | Sample Rate | # of RX Ports | Cost Reference | |
|---|---|---|---|---|
| NI-9230 | 12.8 ksamples/s | 3 | $979 | [51] |
| PCI-1714 | 30 Msamples/s | 4 | $1,429 | [52] |
| PXI-2022 | 250 ksamples/s | 4 | $2,943 | [53] |
| M4i.4451-x8 | 500 Msamples/s | 4 | $13,400 | [54] |
| BittWare RFX-8440 | 5 Gsamples/s | 4 | $18,670 | [55] |

in the case that one would use architectures that do not require an SDR. The radios in Table 4 can be used in place of the SDR in Figure 1 (c). The position of the data acquisition cards in Table 5 are shown in Figure 1 (d).

Two digitizing tuners that we found met the case study requirements for AMT. The SMR 7522 and iWR-6500 are capable of tuning to the IRIG 106 frequency bands and have a sample rate well above 20 Msamples/s. Both of these digitizing tuners are more expensive than the majority of the SDRs we surveyed. This seems to be due to the very wide frequency range that these two radios are capable of receiving.

Three of the data acquisition cards surveyed are suitable based on our case study. The DAQ does not possess any specific tuning requirement because tuning is done by the receiver that performs RF to IF conversion. The only consideration needed is the required 20 Msamples/s. The costs seem high compared to those of the SDRs, especially considering they only perform one function. The SDRs in a comparable price range can compete with the DAQ sample rate while also performing tuning and computations.

## CONCLUSIONS

The survey performed showcases basic capabilities of commercially available SDRs. Out of the SDRs surveyed, 16 meet the requirements of our case study for a telemetry ground station receiver. Costs for these radios ranged from $400 - $280,350 with a median price of $12,191. When comparing these costs to those of digitizing tuners and DAQs, the SDRs tend to be more affordable without sacrificing performance. However, of the SDRs we found suitable in AMT receiving applications, only five of them were clear on having AGC. This is concerning as AGC can be very useful in different AMT applications.

An SDR can perform the function of a tuner, a data acquisition card and the programmable computational engine in many ground station architectures. An external programmable computational engine may be used in certain circumstances, such as the internal computational engine being weak or in the need for an external engine to perform diversity combining for two individual SDRs. In these cases, a digitizing tuner may be used in palace of the SDR.

The real suitability of all SDRs, digitizing tuners, and DAQs are better analyzed through hands-on experimentation. Our data collected through the survey is a reference for quick and basic information on their potential performance in AMT reception.

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