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Determination of Optimum Integration Factors for Digital Integrator of a Microwave Radiometer

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Abstract— Development of ultra-high resolution microwave radiometers involves challenges like implementation of high bandwidth digital receiver section. The signal integration and control module of a microwave radiometer generates all the necessary timing and control signals required for the data acquisition circuitry and integrates signals of all the input channels. Signal integration and dump process required in such total power microwave radiometer can be implemented using analog or digital means. Digital processing offers advantages like programmability, accuracy, better stability, repeatability etc. MADRAS (Microwave Analysis and Detection of Rain and Atmospheric Structures) instrument of ISRO-CNES collaborative Megha-Tropiques satellite is nine channel, five frequency, linearly polarized and self-calibrating microwave imager. For the nine data acquisition channels of MADRAS radiometer it is required to design a generic integrator module. Various design options were studied and simulated to arrive at optimum integration factors for the desired integration time and other system specifications like sampling rate, final resolution etc. for digital integrator of MADRAS payload. This paper gives simulations results, design details and performance analysis of digital integrator of MADRAS microwave radiometer of Megha-Tropiques satellite.

***Index Terms*— Digital Integrator, Integrate And Dump, Microwave Radiometer.**

I. INTRODUCTION

Megha-Tropiques is a satellite mission developed jointly by Indian Space Research Organisation (ISRO) and French Space Agency (CNES). The aim of the mission is to study the water cycle in the tropical atmosphere in the context of climate change. Megha-Tropiques is designed to understand tropical meteorological and climatic processes by obtaining reliable statistics on the water and energy budget of the tropical atmosphere. Three microwave instruments onboard this satellite will allow simultaneously observation of three interrelated components of the atmosphere: water vapor, condensed water (clouds and precipitations), and radiative fluxes. The three instruments are:

MADRAS: Microwave Analysis and Detection of Rain and Atmospheric Studies. This is a microwave imager with conical scanning for studying precipitation and cloud properties.

SAPHIR: Sounder for Probing Vertical Profiles of Humidity. This is a sounding instrument with 6-channels for retrieval of water vapour vertical profiles and horizontal distribution.

ScaRab: Scanner for Radiation Budget. This is a radiometer to measure outgoing radiative flux at the top of atmosphere.

A. *MADRAS Radiometer [1]*

The MADRAS instrument is a multi-frequency scanning microwave radiometer designed to estimate and monitor a number of geophysical parameters related to the ocean and atmosphere. This instrument is a nine-channel, five-frequency, linearly polarized, self-calibrating microwave imager. The main mission applications are listed in the Table-1 below. The channels at 18.7, 36.5, 89.0 and 157.0 GHz frequencies receive both vertically and horizontally polarized radiations whereas the 23.8 GHz channel will receive only the vertical polarisation. The MADRAS instrument is fixed on a structure called PIM (Payload Instrument Module). This structure is designed to provide assembly of all MADRAS instrument subsystems and other two instruments i.e. SAPHIR and ScaRab.

TABLE I. MAIN APPLICATIONS OF MADRAS RADIOMETER

Frequencies	Polarization	Main Application Area
18.7 GHz	H + V	Rain above oceans
23.8 GHz	V	Integrated Water Vapour
36.5 GHz	H + V	Liquid water in clouds, rain above sea
89 GHz	H + V	Convective rain areas overland and sea
157 GHz	H + V	Ice detection in clouds

B. *MADRAS Main Subsystems*

The main subsystems of the MADRAS instruments are:

- MARFEQ – MADRAS RF Equipment
- MSM – MADRAS Scan Mechanism
- MCW – Momentum Compensating Wheel
- MBE – MADRAS Backend Electronics
- PSU – MADRAS Power Supply Unit

MARFEQ – MADRAS RF equipment consists of RF receiver, calibration units including a sky looking reflector and a blackbody target.

MSM – MADRAS scan mechanism rotates the entire MARFEQ assembly at the rate of 25 rpm on a conical surface.

MCW – Momentum compensating wheel is used for neutralizing the disturbances induced by the rotation of MADRAS.

MBE – The MADRAS background electronics carries out the data handling and payload control functions. It is divided into two parts – rotating and static.

PSU – The MADRAS power supply unit is used to power all the RF equipments on MADRAS.

C. MADRAS Backend Electronics (MBE) Architecture

The MADRAS Back-end Electronics (MBE) receives the video outputs from the MARFEQ [2] receivers after gain and offset correction and coarse filtering. The functional architecture of this unit is shown in Fig.1. It mainly consists of signal conditioners, analog to digital converters (ADCs), digital integrators and serializes and associated control electronics. This unit carries out the functions of analog processing of the received video signals, digitization of these video signals and integrating the digitized video signals using digital domain approach. This has the additional functions of configuring the payload as well as providing Telemetry and Tele-Command support for the various subsystems of the MADRAS payload. Following issues were considered in order to arrive at a suitable architecture for the MADRAS Backend Electronics (MBE):

1. The video analog signals from MARFEQ receiver output are very sensitive signals and can be corrupted by external noise and cross talk when they are passed through the Power & Signal Transfer Device (PSTD or slip-rings assembly).
2. Digital signals are inherently better from noise immunity point of view as compared to analog signals.
3. It is possible to achieve sufficient cross-talk specifications and elimination of common mode noise, while passing digital signals through the PSTD still complying with all the other previously stated constraints.

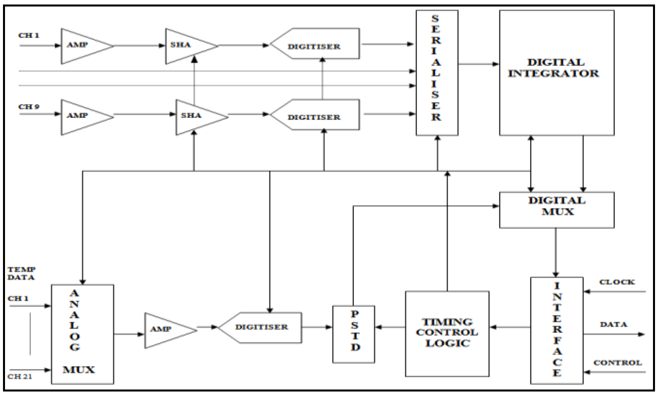


Fig 1 Block Schematic of MADRAS Backend Electronics.

II. DESIGN OF INTEGRATOR

For the MADRAS scanning radiometer, the dwell time (integration time) for the various channels are:

Low Frequency Channels : 16 ms
89 GHz channel : 4 ms
157 GHz channel : 2 ms

These are the theoretically computed values taking into account the nominal values for the orbital height, scan rate, foot print size etc., the integrator may be designed using both analog and digital means [3].

A. Analog Integrator

An analog integrator can be designed using an operational amplifier. Basic integrator circuit using an operational amplifier is shown in Fig.2 below and the corresponding equation of the circuit is given in (1).

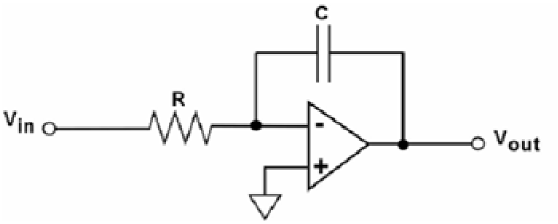


Fig 2 An Analog Integrator using Op-Amp.

$$V_{out}(t) = -\frac{1}{RC}\int V_{in}(t)\,dt \qquad (1)$$

Simulations in MATLAB are carried out to determine the frequency response of above analog filter for different channels of MADRAS radiometer with 16ms, 4ms and 2ms integration times. Simulation results are given in Fig. 3 and tabulated in Table – II below. Fig 1 Frequency Response of Analog Integrator. (a) Low frequency channel with 16ms integration time (b) 89GHz channle with 4ms integration time (c) 157GHz channel with 2ms integration time

TABLE II ANALOG INTEGRATOR RESPONSE

Channel	Integration Time / RC Filter Time Constant (ms)	-3dB Frequency (Hz)
Low Frequency	8	20
89 GHz	2	80
157 GHz	1	160

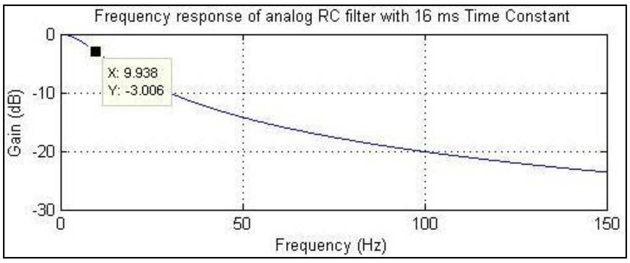
Even though the integrator circuit may be realized using above op-amp circuit, it has some inherent disadvantages.

Disadvantages of Analog Integrator:

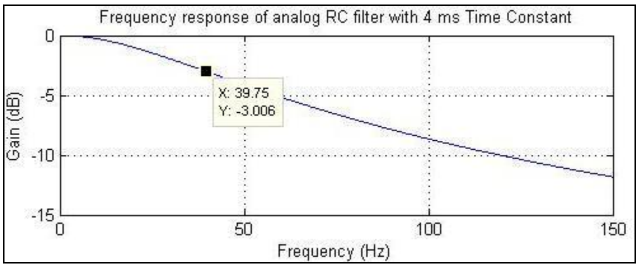
- **Offset Error:** Op-amp gives some offset signal at its output even though there is no input signal. This offset creates error in the actual output of the op-amp when signal is present at its input.
- **Leakage Current:** All transistors / MOSFET devices have inherent leakage current. This leakage current tends to interfere with the actual output and corrupts the signal.
- **Long Term Stability:** Over a long period of operation offset and leakage current of an op-amp tends to change which causes variations in output.
- **Temperature Drift:** Temperature variations also cause variations in offset and leakage current of op-amp.

Due to these disadvantages an analog integrator is not preferable. A digital "equivalent" implementation offers some advantages over analog circuitry including the ability to be dumped in an extremely short time with no overshoot

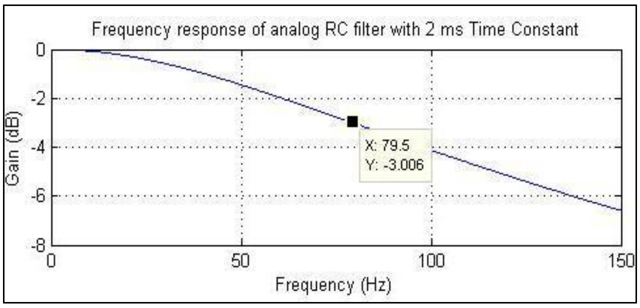
Freedom from drift, and the use of digital ICs or a computer for processing.



(a)



(b)



(c)

B. Digital Integrator

Integration in time domain is equivalent to a filter in frequency domain. The time domain equation of an analog integrator and its equivalent in frequency domain are shown (2):

$$V_{out}\ (t) = -\frac{1}{RC}\int V_{in}\ (t)dt \Longleftrightarrow V_{out} = -\frac{V_{in}}{jwRC} \qquad (2)$$

Time Domain Frequency Domain

The frequency domain equation represents a filter with following specifications:
Magnitude: -20dB/decade
Phase: 90° phase shift for all frequencies

This filter is easy to implement in a digital signal processor.

III. DETERMINATION OF OPTIMUM INTEGRATION FACTORS FOR DIGITAL INTEGRATION

A. Sum and Dump Algorithm

The digital filter is designed primarily to provide the necessary dynamic loop behavior for optimum control of the noise injection process. The concept used to reduce the variance of the data in the post loop processor is well known sample mean algorithm [4][5][6]. This process will hereafter be denoted as a "sum- and- dump" algorithm due to its close similarity to the integrated and dump circuit used in analog matched filter and estimation system. Indeed mathematically the behaviour of the sum and dump algorithm on a discrete time basis is virtually identical to the behaviour of the integrated and dump filter on a continuous time basis.

The steady state frequency response of a discrete time sum and dump filter, denoted as $H_N(f)$, is given in (3):

$$H_N(f) = \frac{\sin(NwTo/2)}{N\sin\,(wTo/2)}\, e^{-j(N-1)wTo/2} \qquad (3)$$

The equivalent one-sided noise bandwidth B_N can be expressed as

$$B_N = \int_0^{0.5\, f_{os}} [H_N(f)]^2\, df \qquad (4)$$

Where, $f_{os} = 1 / To$

Substituting H_N (f) from (3), the value of this integral is

$$B_N = \frac{2^{-[\log_2 N+1]}}{T_o} \qquad (5)$$

$$= \frac{1}{2NT_o} \qquad (6)$$

Let $\tau = NT_o$ = total time interval for integration. Substituting these values of τ in (6), the one sided equivalent noise bandwidth is:

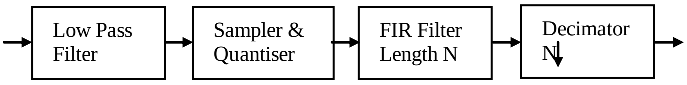
$$B_N = \frac{1}{2\tau} \qquad (7)$$

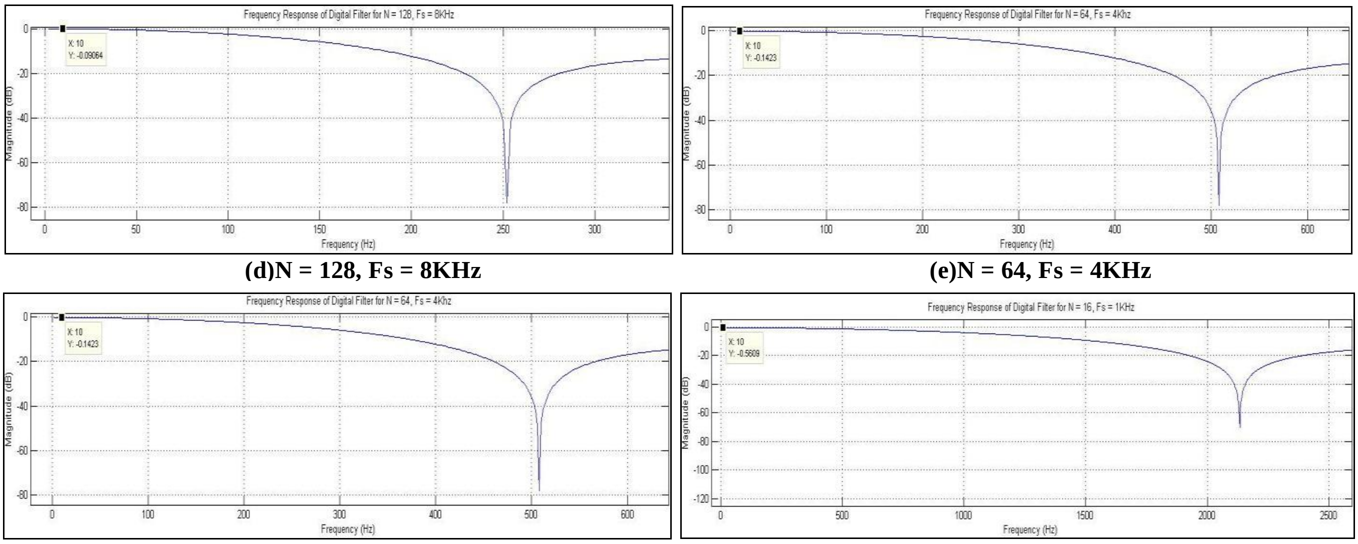
This result is exactly the same as for the continuous time integrate and dump filter with τ as the integration time. Thus, the sum and dump algorithm for a discrete time signal functions exactly the same as the integrate and dump filter for a continuous time signal provided that the summation Interval in the discrete time case is equal to the integration interval in the continuous time case. This would imply optimum sampling at the Nyquist rate for the discrete time system.

B.Implementation of Sum and Dump Algorithm

The digital implementation inherently requires that the input waveform be sampled and "folding" of the noise spectrum will greatly reduce the filter effectiveness unless a low-pass pre-filter is used to limit the input bandwidth [7]. The front-end receiver output in MADRAS radiometer has a low pass filter with the following characteristics: 2.5 KHz cut off (-3 dB) and 20 dB / decade roll off. Block schematic of digital implementation of integrate and dump filter is shown in Fig.4. fc = 2.5KHz Min. fs = 5KHz N = 128/64/32/16

The output of the MARFEQ low pass filter is first sampled, digitized and then integrated with a FIR digital filter. The output of this filter is appropriately down sampled (decimated) after the filtering operation depending on the integration time requirement of that particular channel.





(d)N = 128, Fs = 8KHz (e)N = 64, Fs = 4KHz

(f) (g)N = 16, Fs = 1KHz

Fig 5. Frequency Response of Digital Filter for Low Frequency Channels with 16ms Integration Time

C. *Digital Filter Response*

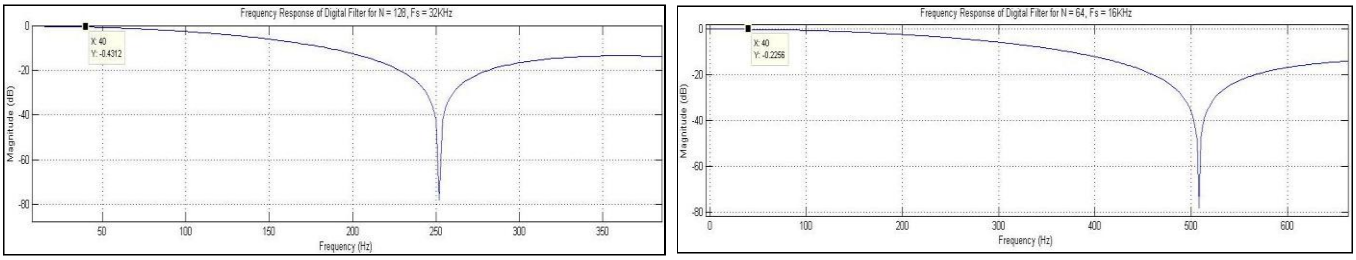
Frequency response of the digital integrator for different channels of MADRAS radiometer is simulated using MATLAB software. Simulation results are shown in Fig.5, 6 and 7 and tabulated in Table – III, IV and V below.

TABLE III. 89 GHz Channel Digital filter Response

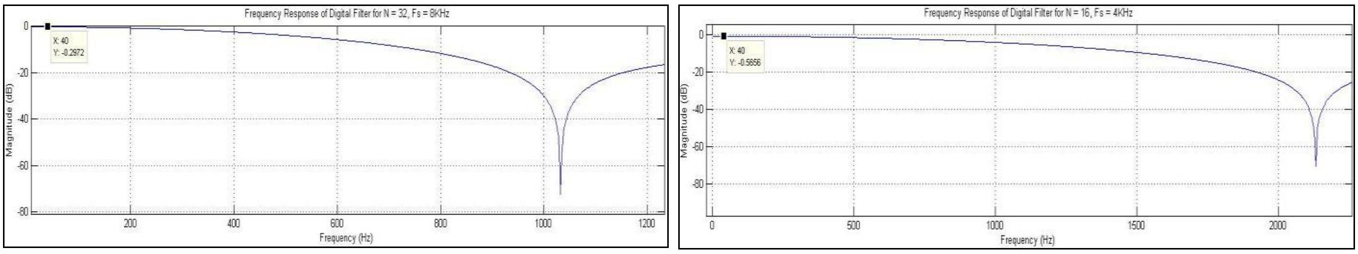
No. of samples integrated	Sampling rate (KHz)	Magnitude (dB) at 40Hz (equivalent to -3dB freq. of analog filter)	Freq. at -3dB (Hz)	Magnitude (dB) At lowest point
128	32	-0.431	112	-78.13 at 252Hz
64	16	-0.225	220	-78.2 at 508Hz
32	8	-0.297	438	-72.3 at 1032Hz
16	4	-0.565	860	-70.6 at 2134Hz

TABLE IV. LF Channels Digital filter Response

No. of samples integrated	Sampling rate (KHz)	Magnitude (dB) at 10Hz (equivalent to -3dB freq. of analog filter)	Freq. at -3dB (Hz)	Magnitude (dB) At lowest point
128	8	-0.090	112	-78.13 at 252 Hz
64	4	-0.142	220	-78.2 at 508 Hz
32	2	-0.277	438	-72.3 at 1032 Hz
16	1	-0.560	860	-70.16 at 2134Hz

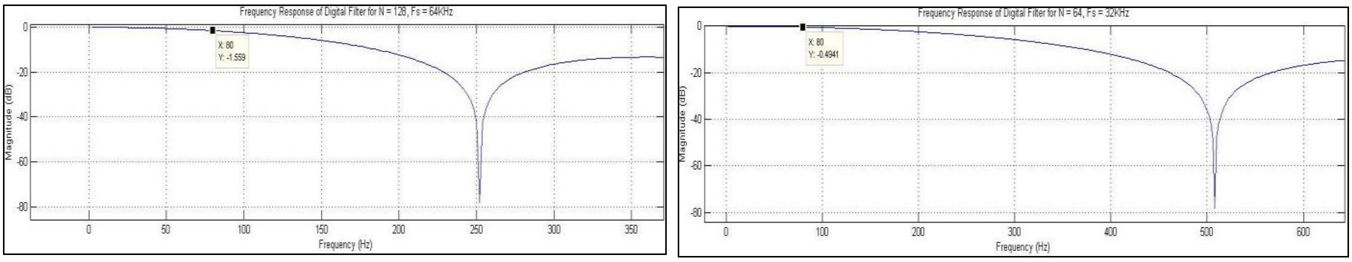


(a) N = 128, Fs = 32KHz **(b)** N = 64, Fs = 16KHz

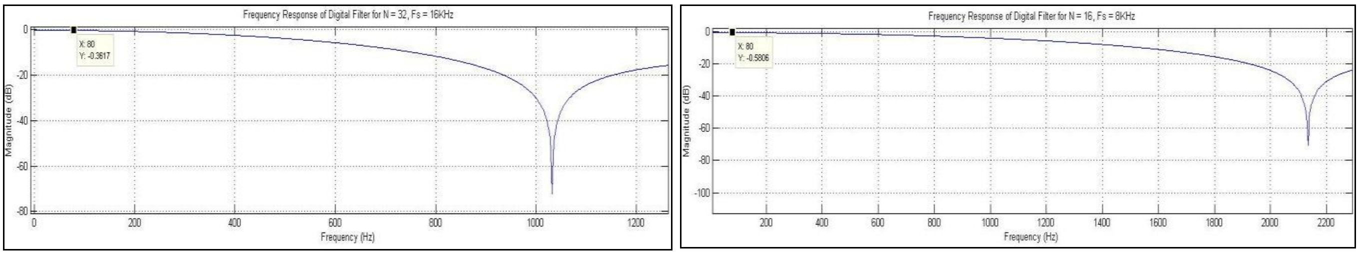


(c) N = 32, Fs = 8KHz **(d)** N = 16, Fs = 4KHz

Fig 6. Frequency Response of Digital Filter for 89 GHz Channel with 4ms Integration Time



(a) N = 128, Fs = 64KHz **(b)** N = 64, Fs = 32KHz



(c) N = 32, Fs = 16KHz **(d)** N = 16, Fs = 8KHz

Fig 7. Frequency Response of Digital Filter for 157 GHz Frequency Channel with 2ms Integration Time

TABLE V. 157 GHZ CHANNEL DIGITAL FILTER RESPONSE

No. of Samples integrated	Sampling rate (KHz)	Magnitude (dB) at 80Hz (equivalent to -3dB freq. of analog filter)	Freq. at -3dB (Hz)	Magnitude (dB) At lowest point
128	64	-1.56	112	-78.13 at 252Hz
64	32	-0.494	220	-78.2 at 508Hz
32	16	-0.361	438	-72.3 at 1032Hz
16	8	-0.580	860	-70.6 at 2134Hz

IV. DISCUSSIONS

Comparing the performance of digital filters with analog filters in Tables – II, III, IV and V, it is observed that the performance of digital filters is better than analog filter. The -3dB frequencies for analog filters are 10Hz, 40Hz and 80Hz for LF, 89GHz and 157GHz channels respectively whereas the -3dB frequencies for the corresponding digital filters are above 100Hz for all the three frequency channels. There is very little variation in the performance among the simulated digital filters for different integration factors and corresponding sampling rates, hence any of the combinations of number of samples and sampling rate can be used for a particular given integration time. The bandwidth of the filter preceding the digital integrator is 2.5 KHz, so according to Nyquist criterion the minimum sampling rate can be 5 KHz, therefore, the 1 KHz, 2 KHz and 4 KHz sampling rates options cannot be used for low frequency channels. Similarly, 4 KHz sampling rate option cannot be used for 89 GHz channel. For 157 GHz channel all sampling rates are above the Nyquist sampling rate of 5 KHz and hence all can be used. Hence, the minimum sampling rate for all the channels is 8 KHz and the optimum integration factors corresponding to 8 KHz sampling rate for LF channels, 89 GHz channel and 157 GHz channel are 128, 32 and 16 respectively.

V.CONCLUSION

The digital integration and control module of a microwave radiometer carries out the functions of analog processing of the received video signals, digitization of the video signals and integrating the digitized video signals using digital domain approach. An analytical and simulation model of analog and digital integrators has been developed to compare their frequency response and to arrive at optimum integration factors for the digital integration of different channels of MADRAS radiometer. Simulation results showed that performance of digital integrator is much better than analog integrator over wide frequency band. To avoid aliasing, the minimum sampling rate for all channels is 8 KHz and the optimum integration factors corresponding to 8 KHz sampling rate for low frequency channels, 89 GHz channel and 157 GHz channel are 128, 32 and 16 respectively.

VI. ACKNOWLEDGMENT

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