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Arduino-based high-frequency radio telescope and observations

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Abstract

This is a pilot project undertaken by the UG and PG students of the Department of Physics, St. Xavier's College (Autonomous), Kolkata under the supervision of Dr. Suparna Roychowdhury and Dr. Shibaji Banerjee and with the assistance of Mr. Bappaditya Manna, Technical Officerof Father Eugene Lafont Observatory (FELO) on building a low-cost high-frequency radiotelescope using Arduino.This paper presents the design of the smallArduino-based radio telescope recently developed by the group to observe radio emission at high frequencies (12-18GHz)and the initialobservations including detection of geostationary andnon-geostationary satellites.Preliminary results demonstrate the effectiveness of this Arduino-based radio telescope in the eraof large radio telescopes that are inaccessible to students. As the radio telescope operates in ahigh-frequency range, it is easier to observe in city areas where Radio Frequency Interference(RFI) is a significant issue. The system can be pointed either manually or using a computerized mount to any radio source and data can be collected from a satellite finder as well asfrom Arduino micro-controller. This system can be used for a basic understanding of radioastronomy and for training purposes for University and College students at a very lowcost. Further, we would also like to extend this to a two-element radio interferometer andundertake interferometric observations of astronomical radio sources in future.

Keywords: *Radio astronomy, Radio telescope, Satellite, Ku band, Sun.*

1. Introduction

Early astronomy mainly relied on visible light observations for studying the vast Universe. This provided only a glimpse of this mysterious Universe. With the birth of radio astronomy in the mid-20th century, humankind came to know about the remaining parts of the electromagnetic spectrum, that narrates many untold stories of the invisible cosmos.The intense development happened between 1955 and 1960, afterwards radio astronomy flourished in many countries. Radio telescopes are excellent for investigating scientific phenomena of the Universe. From the study of Pulsars, Quasars, Cosmic Microwave Background Radiation, galaxy distribution to 21cm cosmology, radio astronomy opened door to all these significant studies.

Despite of having significant contribution to our understanding of the Universe, radio telescopic observations come with challenges that makes it inaccessible to most students and researchers. The cost for building or accessing such radio telescopes is one of the barriers. The lack of financial investment for building and maintaining such advanced instruments and complexity of developing sophisticated data receiving and processing systems makes it hardly imaginable to beginners. So, these factors constrain the number of researchers who are able to engage in with these powerful instruments. Only someof the institutions provides the required infrastructure and opportunity to beginner level researchers in the field of radio astronomy. This significantly reduces the scientific progress, limiting the study and publications in this field.

Radio frequency Interference (RFI) is one of the most significant factors while planning for the radio observational sites. Radio quiet areas are best for astronomical radio observations. This makes it impossible to plan radio observation in the lower frequency range from Metro cities. Its important to plan a frequency range that avoids RFI, can be operated from city areas and is significant for astronomical observation. High frequency range (10-20 GHz) gets least affected by the city RFI. Sun being a broadband transmitter, emits radio waves in this range too. Students can have a first-hand experience of spotting radio sources like geostationary and non-geostationary satellites and signal processing. Its essential to understand the amplification and filtering process through simpler models rather than directly diving into complex sophisticated machineries. These motivates in developing a low-cost high frequency radio telescope with simpler circuits and easily accessible components.

Our simple radio telescope offers an opportunity for the masses to have a deeper insight into astronomy by making the technology readily available at a very nominal cost. It uses components which one can readily access from electronics stores. This small Arduino based radio telescope can observe radio emissions from the solar chromosphere at high frequencies (10.7-18Ghz). As the sun is a broadband transmitter,its radiations can be easily detected with this setup.*Gireesh, G. V. S., et al.* [1],Latief, Tauriq,et al. [2] and*Herrera, Daniel E., et al.* [3]demonstrated the design and solar observational results of radio interferometerwith commercial dish antennas. Preliminary results demonstrate the effectiveness of this radio telescope in an era of large radio telescopes.*Mastour, Abubakar, et al.*[4]tested the Affordable Small radio telescope model originally developed by NCRA, TIFR. *Bhal Chandra et al.* [7] shows how ASRTcan be instrumental in letting university and college students get a taste of the true flavors of radio astronomy and the wide range of explorables offered by it. This paper broadly describes the design and preliminary results of our Arduino-based radio telescope, that we developed with rather simpler electronic components that are easily available. There is hope that the benefits of radio astronomy can now be more widely shared, enabling a broader spectrum of minds to contribute to the unraveling of cosmic enigmas.

2. Antenna and Receiver system

The basic hardware elements of every radio telescope are the antenna and receiver system. The selection of the antenna, as well as the effective execution of the receiver system, are significant components of radio astronomical observations that are based on the specific observational targets and frequency range. We intend to utilise TV dish antennas which operates in a range of 10.7-18 GHz and are easily available in the market for this project.

2.1 Antenna system

The choiceof the antenna system is of utmost importance in our project to build an Arduino-based radio telescope keeping in mind the goal of developing a cheap radio telescope. Figure 1 shows a parabolic dish reflector that we chose, namely the commercial dish model STC 11-04 from SUN DIRECT HD. The dish's natural paraboloidal form provides remarkable capabilities for capturing and focussing radio frequency (RF) signals emitted by high frequency radio sources, was the primary factor in this decision. With a diameter of 60.5cm, the dish is capable in gathering RF signals from astronomical sources. The dish’s depth is 5cm that contributes to the structural integrity and helps in precise focussing.

FIG 1: The commercial TV dish antenna model STC 11-04 used in Father Eugene Lafont observatory for Arduino-based radio telescope project

This project explores the microwave spectrum, specifically targeting the frequency range of 10.7-18 GHz. This corresponds to the Ku band of the electromagnetic spectrum which is the carrier frequency in Satellite TV communication. Aperture efficiency (η) for dish antenna is 0.55 (Baars, Jacob WM [6]), takes into account the losses and inefficiencies in the antenna's construction. Now, considering this, the Effective area is given by

$$A_{eff} = \eta * Area = 0.15811m^2$$

Where Area is the aperture area of the dish antenna.

Directivity is the ratio of the radiation intensity in a specific direction to the average radiation intensity over all directions. Mathematically Directivity(D) it is given by,

$$D = 10log_{10}\left(\frac{4\pi A_{eff}}{\lambda^2}\right)$$

For A_{eff}=0.15811 m^2 and λ=2.8cm, D=34dB.

The gain of an antenna is a measure of its ability to direct or concentrate energy in a particular direction given by,

$$G = 10log_{10}\left(\frac{4\pi\eta A_{eff}}{\lambda^2}\right) = 31.44dB$$

The beam width of a radio telescope is the angle between the direction corresponding to the half maximum power or so-call the half power beam width (HPBW). So, the circular aperture for dish beam width is given by θ,

$$\theta = 58.4 * \left(\frac{\lambda}{D}\right) = 2.703radian$$

Our parabolic satellite dish is already equipped with a receiving device, LNB (Low Noise Block). It is a filter which passes only the required band of the frequency spectrum and cuts off all other frequencies in the output, and is also responsible for receiving and amplifying signals keeping noise levels as low as possible. It also works as a downconverter, converting higher frequency signals to lower frequencies making easier to transmit through coaxial cable.

2.2 Receiver system

The receiver system consists of the technical core that transforms the received RF signal into meaningful data for further analysis. Large radio telescope systems use costly and very sophisticated receiver systems for amplifying and filtering the RF signal which consists of quite complex electronic elements. For this kind of small projects that aims at giving College and University level students, a first-hand exposure to radio astronomy, must be developed with rather simpler, cost effective and readily available alternatives.

Fig 2 shows a satellite finder, also known as a satellite meter or satellite signal meter, is a device used by engineers to detect satellite signal strength and to align the dish accurately. It is of two types: Analog and Digital. In our case, we used an Analog satellite finder (which was readily available in the market) in our project to record the radiation intensity of the sun during its passage (since we are using a fixed-mount for now) and by noting the amplitude (in our plot), we can easily determine whether our sun is active or calm. The satellite finder (connected to the LNB) detects the signal from the LNB and gives a meter indication of the signal strength. It also changes the frequency with the change in intensity of the signal (*Mohsin Madki, Dr. B.C.Joshi*[12]).

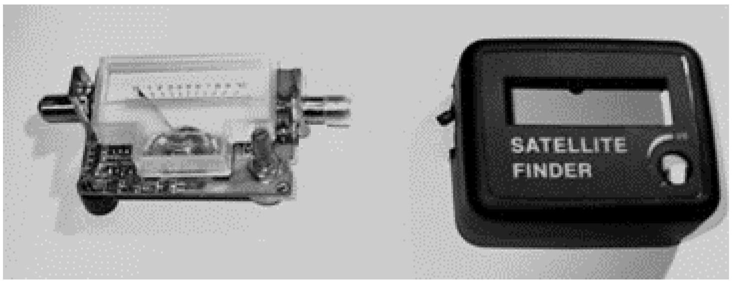

Fig 2: SF-95 Analog satellite finder used for the Arduino-based radio telescope project. (Image source: [11])

After having the amplified and filtered Analog signal from the parabolic dish antenna, next step is to convert these Analog waveforms to digital format. Most of the microcontrollers in market come with built in 10-12 bits ADC pins, but they lack high precision. In our project, the data from the antennas will be received in form of voltage magnitudes which are Analog values. To measure and feed those values to a computer we need a high accuracy Analog to digital converting module.

ADS1115 [Fig 3] module is an Analog to digital converter module that has 16-bit resolution and can measure a maximum 5 volts. This module uses I2C communication protocol, so it has a high speed and occupies a small number of the microcontroller pins.

- Initially a multiplexer selects the input signal.
- The selected signal feeds into a Programmable Gain amplifier (PGA).
- The PGA can be programmed to provide amplification of small signals prior to conversion.
- Subsequently, the input is converted by a 16-bit Delta Sigma converter.
- The converter uses its own built-in voltage reference and built-in oscillator in measuring the input signal.
- Finally, the result of the conversion goes into the I^2C interface.

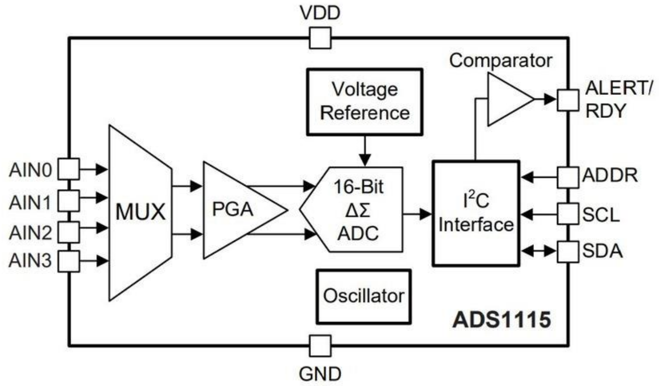

Fig 3: Schematic diagram of ADS1115 Analog to Digital converter. (Image Source: [8])

Next, the digitized signal is directed to the microcontroller which serves as the brain of our Arduino-based Radio telescope. We have to first interface our microcontroller (Arduino Uno),with the ADS1115 module.

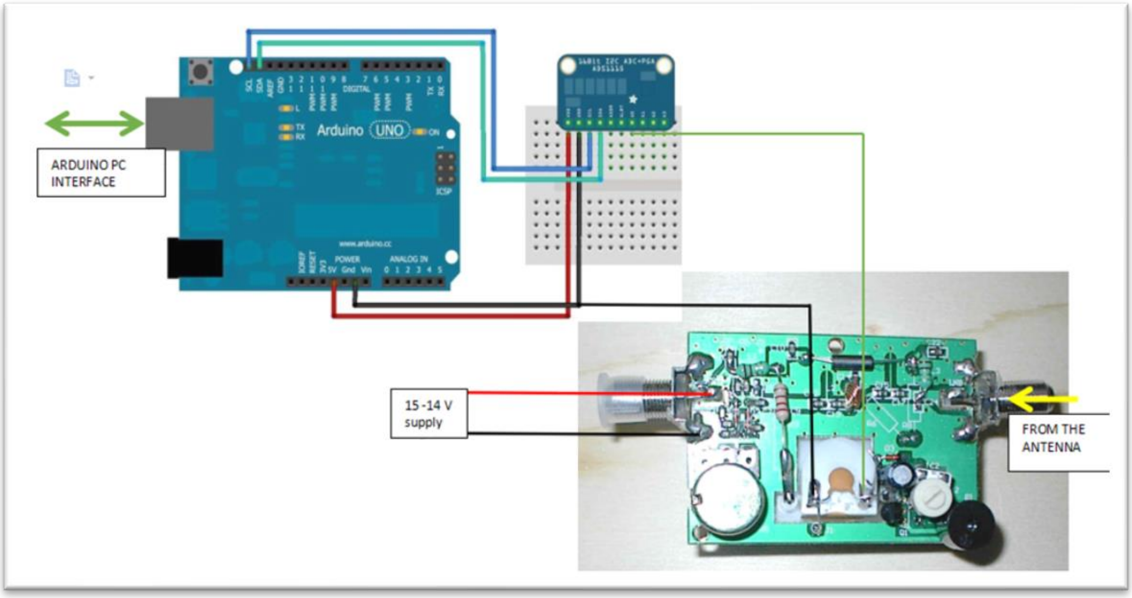

Fig 4: Circuit Diagram of the receiver system of the Arduino-based radio telescope. (Modified from [13])

Two libraries were used to interface Arduino Uno with the ADS1115 module, namely **Adafruit_ADS1X15.h** and **Wire.h**([9]). Adafruit_ADS1X15.h includes the Adafruit ADS1X15 library, which provides functions to interface with the ADS1115 ADC.Wire.h includes the Wire library, which is used for I2C communication. After successfully interfacing the ADS1115 16-Bit ADC module and Satellite finder with Arduino, enabling high-precision Analog measurements, the I2C communication protocol ensures fast data transfer. The circuit diagram (Fig 4), libraries, and sample code assist in accurate voltage measurement. The Arduino code reads a single-ended Analog input (AIN0) and prints the converted digital value to the serial monitor every second.

In the Arduino code, an instance of the Adafruit_ADS1115 class is created named ads1115. **Serial.begin(9600)** initializes serial communication with selected port at baud rate of 9600. Various print statements are there for initialization messages. **ads1115.begin()** initializes I2c communication with the ADS1115 on its default address 0x48. **ads1115.setGain(GAIN_EIGHT)** sets the gain of the ADC to 8x, which corresponds to a range of +/- 6.144V. Satellite finder was connected to A0 pin of ADS1115 which is further connected to an Arduino Uno as in the diagram (Vdd - 5V, Gnd - Gnd, SDA/SCL - SDA/SCL), all powered from the USB on a PC ([10]). It reads the A0 pin where the sat finder is connected by:**ads.readADC_SingleEnded(A0).**

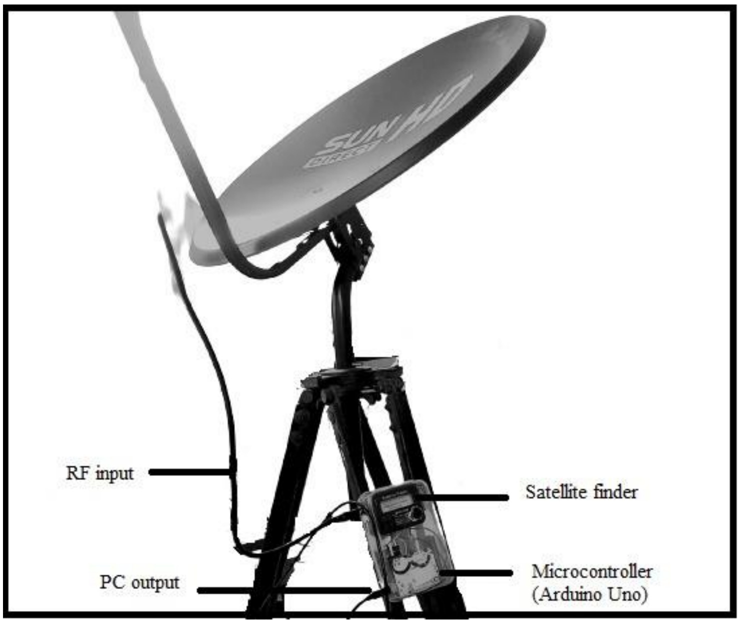

Fig 5: Complete Arduino-based radio telescope system at FELO, Kolkata

For scaling the output plots according to user's needs, **matplotlib** and **serial** libraries can be used for real-time plotting. We define two list x_data and y_data to store the values of real time and serial values. Then we define a function update.plot(), which is used to plot the list of serial data after an iteration.

For now, we are using a fixed telescope mount (which can be used to point manually) for our project. Later in our project, we will also use an equatorial mount which will automatically track the sun, thus helping us automate the whole process of taking readings.

3. Observations

Observations can be carried out eitherusing fixed mount or with fully computerized mount for precisely tracking the astronomical object. For initial observation we used a fixed mount and manually pointed the radio telescope towards radio sources. Geostationary and non-geostationary satellites can be detected by this radio telescope under various atmospheric conditions. Geostationary satellites remain fixed relative to a point on Earth's surface. Valuable information about signals and interactions with the space environment of the geostationary satellite can be gained by radio observation. The frequency range of 10.7 to 18 GHz falls under Ku band which is commonly used for satellite communication. Satellites use Ku band for downlink and uplink communication with ground stations.

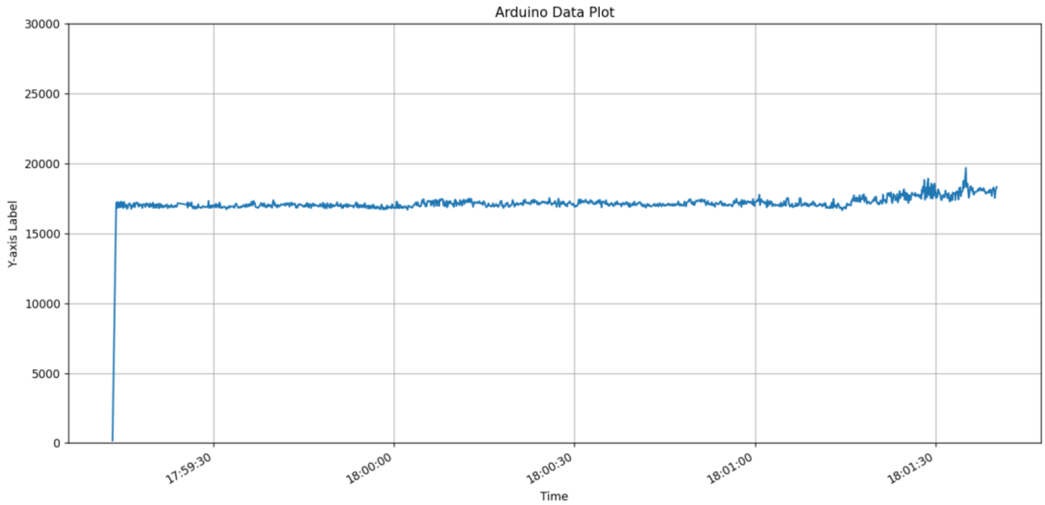

Fig 6: Signal strength vs Time plot of the radio telescope. Peak representing the detection of Starlink 5387 satellite

Non-geostationary satellites like Starlink by SpaceX, that aims to provide global internet coverage by deploying thousands of satellites in low Earth orbit (LEO), can be easily detected by the Arduino-based radio telescope system. Figure 6 shows signal strength vs time plot, where the peak represents the detection of some radio source. Initially we tracked the path of all satellites simultaneously while taking the RF data. This confirmed the detection of Starlink 5387 on 11th August, 2023 from Father Eugene Lafont Observatory. On the same day we scanned different regions of sky and detected 20 Starlink satellites.All the data were taken setting the gain in satellite finder to 8 dB.

Figure 7 shows the peak representing the detection of NATO 3dr which is classified as a Geostationary satellite.The satellite signal strength is usually constant and that can be used to calibrate the solar radiation.

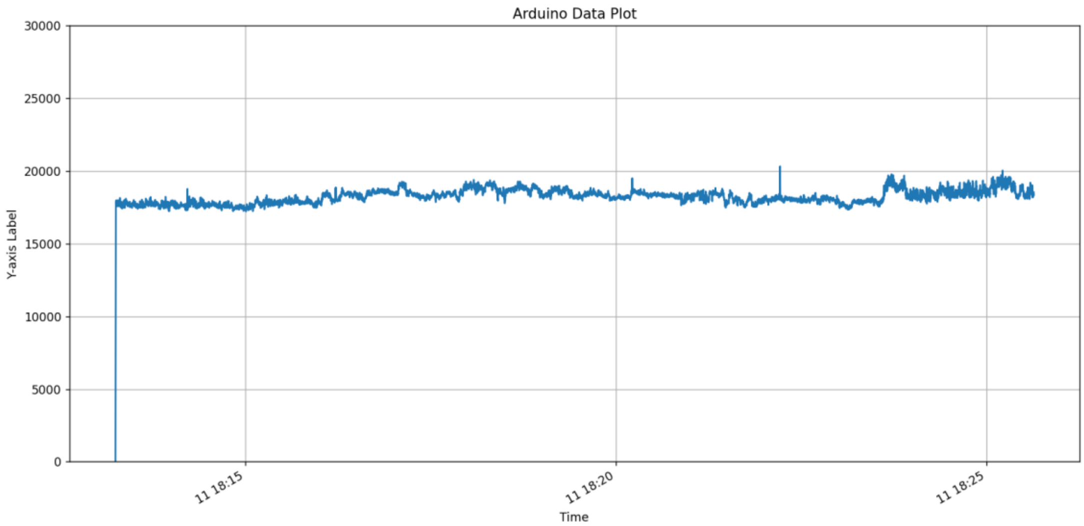

Fig 7: Signal strength vs Time plot of the radio telescope. Peak representing detection of NATO 3dr satellite

Sun direct DTH uses Measat 3 and GSAT 15 that can also be detected moving the radio telescope to 91.5 degrees East and 95 degrees East. Various other geostationary satellites can be detected including INSAT (3A, 4B, 2E, 3B, 4A), NSS 6, Thaicom (2,5), ABS1, Intelsat 12, and Express-Am2.

Table 1: Below table contains all the satellites detected by the Arduino-based radio telescope with time and position on 11th August,2023 from Father Eugene Lafont Observatory:

Satellite	Time (IST)	Type
Starlink 5312	17.30	Non-geostationary
Starlink 1705	17.40	Non-geostationary
Starlink 5382	17.47	Non-geostationary
Starlink5434	17.48	Non-geostationary
Starlink 5744	17.54	Non-geostationary
Starlink 1597	18.00	Non-geostationary
Starlink 5387	18.01	Non-geostationary
Starlink 1615	18.05	Non-geostationary
Starlink 5002	18.08	Non-geostationary
Starlink 4146	18.09	Non-geostationary
Starlink 1629	18.10	Non-geostationary
Starlink 4066	18.11	Non-geostationary
Starlink 1498	18.14	Non-geostationary
Starlink 1608	18.17	Non-geostationary
Starlink 3530	18.18	Non-geostationary
Starlink 1619	18.19	Non-geostationary
Starlink 4103	18.20	Non-geostationary
NATO 3dr	18.25	Geostationary
Starlink 6091	18.30	Non-geostationary

Apart from satellite detection, the group also tested by moving around the radio telescope and recorded changes in the peak of the signal strength vs time plot.

Sun is a broadband transmitter. This Arduino-based radio telescope can be used for studying radio emissions from sun's chromosphere. It is possible to examine the variations in solar radiation by continuously monitoring it. The group couldn't take sufficient solar data because the sky remained mostly cloud covered in the month of July and August. While setting the satellite finder gain to 4dB, when we moved the radio antenna towards Sun, we observed change in the Satellite finder reading and also noticed small change in the peak of the signal strength vs time plot. For better data and solar observation, we need cloudless sky.

4. Conclusion

For recording faint astronomical radio signals, large sophisticated radio telescopes are necessary but those radio telescopes are used for serious research by scientists in the field of radio astronomy. These facilities are mostly inaccessible to college and University students, and there’s a need of rather simpler and cheaper alternatives for basic studies and research in this field. Arduino-based radio telescope used standard TV dish antenna with its LNB as the antenna system and Arduino based circuit with satellite finder for receiver system. Using these alternatives, the group successfully developed a cheaper and simpler version of radio telescope that can successfully detect radio sources like geostationary and non-geostationary satellites, Sun and also detects human body around it. Using radio antenna that operates in the frequency range of 10.7-18GHz comes with additional advantage that the signal at this range is least affected by Radio frequency interference(RFI) which is a very significant factor while taking data from metro-cities like Kolkata. The group planned further additions of differential amplifier and filters to the circuit for better data.

5. Acknowledgements

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