

A CRYOGENICALLY COOLED, SEVEN BEAM, 21 CM WAVELENGTH RECEIVER

FRONT END FOR THE ARECIBO RADIO TELESCOPE

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ABSTRACT

A 7-beam receiver, using a cryogenically cooled front end for maximum sensitivity, has been developed by the Commonwealth Scientific and Industrial Research Organisation's (CSIRO) Australia Telescope National Facility (ATNF) Engineering and Development Group and is almost wholly fabricated using the facilities of the ATNF and Australian industry. This new receiver system was recently installed in an antenna situated in Puerto Rico. This paper highlights various design and construction details of the front end, and reports the results of laboratory and telescope testing of the front end cryogenic and electronic systems. This paper also describes measures to minimise self-generated electromagnetic interference (EMI) and shield the receiver from high power radar in close proximity to its location in the receiver room of the Gregorian dome.

INTRODUCTION

The United States based National Astronomy and Ionospheric Center's (NAIC), 305m-diameter Arecibo Observatory radiotelescope, operated by Cornell University for the National Science Foundation, is situated in Puerto Rico and is physically the largest and, in some wavelength bands, the most sensitive single dish radio telescope in the world [1]. It is used to study large numbers of sources that are too faint to be seen with other telescopes. The outstanding science achieved with the 13 beam multifeed receiver [2] used on the CSIRO ATNF's 64m-diameter radiotelescope situated at Parkes in central west NSW was the trigger for NAIC to approach the ATNF in order to have the ATNF receiver group construct a multifeed receiver for the Arecibo dish. The Arecibo L-band Feed Array (ALFA) was the name given to this seven feed system that will allow large-scale surveys of the sky to be conducted with unprecedented sensitivity using the Arecibo telescope. The complete ALFA system, operating near 1.4 GHz, consists of a cluster of seven cooled dual-polarization receivers, a fibre-optical transmission system, and digital back-end signal processors. The system will enable deep surveys for a variety of objects in the Milky Way Galaxy and other galaxies for probing cosmology. As such, the multibeam system will have a broad appeal to astronomers from all over the world.

THE 7 BEAM RECEIVER SYSTEM

Receiver Electronics

The receiver has the basic form of a low-noise 14-channel system with both a conversion system and high-resolution spectrometer back end supplied by NAIC. Outputs from a 7- element feed-horn array couple via circular waveguides into a cryogenic cryostat where 14 low-noise preamplifiers, 1 for each polarization, and cooled to 12 K, provide an initial 37 dB of gain across a 1200-1800 MHz band with an excess noise contribution of about 5K. The 14 preamplifier outputs are passed through the cryostat walls via a hermetic coaxial connector bulkhead. The required band of observation is 1225 MHz to 1525 MHz and the band defining filters are within the NAIC backend.

THE FEED SYSTEM

There were two major drivers that determined the outcome of the feed array design study undertaken by Trevor Bird [3] of CSIRO's Telecommunications and Industrial Physics Division (as it was at the time). Firstly the feed elements had to

efficiently illuminate the subreflector for low spillover which implies a high edge taper. Arecibo has a Gregorian system with the tertiary reflector edge at an angle of 60 degrees with respect to the optical axis. The second driver was the feed aperture diameter was limited in size, since the larger the diameter the further the beams are apart and the greater the scan loss. With a scan loss of 1.5 dB considered an upper limit the feed centre to centre spacing was constrained to be <270 mm. A variety of circular and coaxial horn geometries were investigated and after detailed study by CSIRO and NAIC it was concluded that the largest apertures tended to give best overall performance and that the TE₁₁-mode stepped horn offered the best compromise in performance in terms of spillover efficiency, antenna noise temperature and sensitivity [4].

The final design consists of 7 stepped circular horns arranged in a hexagonal pattern, the apertures of which are located on the telescope focal plane, and couple directly into the cryostat interface through circular waveguide vacuum windows. The front of each feed has a thin (0.14 mm) sheet of Fluorglas to protect against airborne impurities and wildlife. Because of the tropical climate, the facility of introducing dry gas into the space between vacuum window and Fluorglas was included using gas-pipe nipples that protrude from the feed and these nipples can be connected via a manifold. A plan view of the feed horn aperture plane is shown in Fig. 1 and a photograph in Fig. 2.

An EMI-tight shroud was added around the feed array that takes the form of a can with EMI gaskets at both ends. It is a three part structure with a whole cylinder attached to the cryostat and another larger diameter cylinder split in two lengthways to allow easy installation between the whole cylinder and an aperture plane plate. It's position means the whole feed array and input waveguide to the cryostat is surrounded. Additionally a plate was supplied to bolt to the front of the feed array with additional EMI gasket to seal around each feed. The plate is manually installed when required as a suitable measure to protect the system during use of the high power radar transmitters.

THE CRYOGENIC FRONT END

The complete front end consists of the feed-horn array, the cryogenics cryostat containing cooled orthomode transducers and high electron mobility transistor (HEMT) amplifiers, a local monitor and control box and two outrigger, multipurpose electronics modules which contain support electronics, HEMT amplifier bias supplies and a comprehensive monitoring system. The monitoring system indicates the bias states of all transistors in these 14 cooled HEMT amplifiers, as well as temperature and vacuum information on the cryogenic system performance.

The cryogenic front end (Fig. 3 and Fig. 4) is situated right at the focal plane area of the telescope optics. It has been

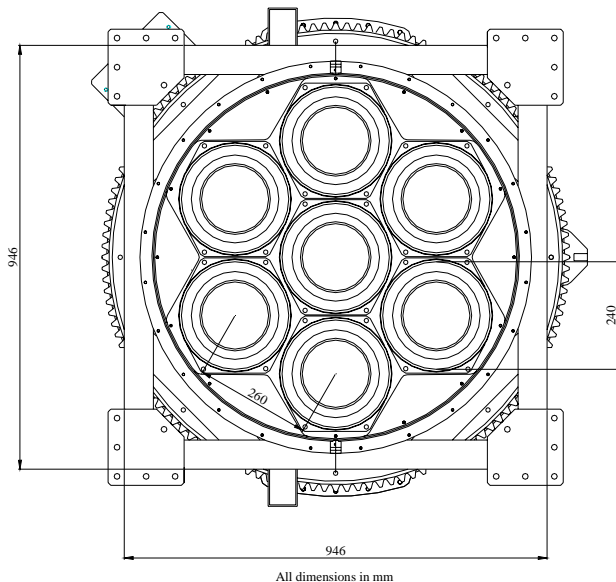


Fig 1. Plan view of the 7-beam feed-horn array aperture plane. Note the horn spacing of 260 mm and the horn aperture diameter of 240 mm.

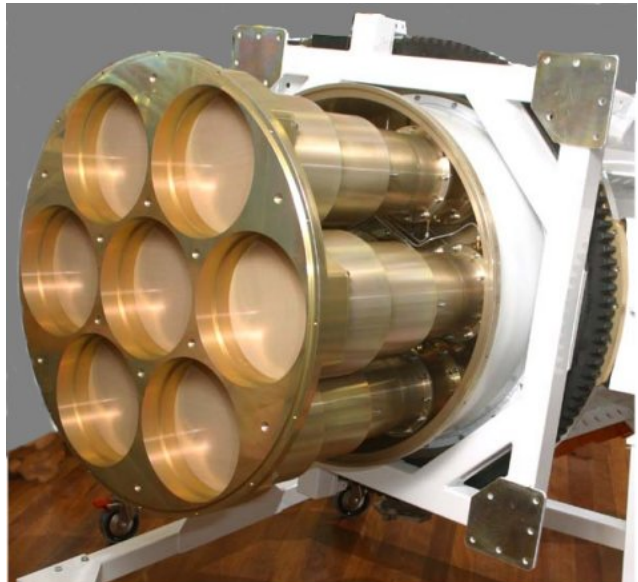


Fig 2. Photo of the assembled array with the lower section of the EMI shroud removed to show the feeds.

constructed as a removable entity for repairs and maintenance. The package is mounted on a 1 m diameter slew ring turned by a pinion gear attached to a brushless DC motor. A winding/unwinding energy chain (cable snake) carrying signal cables and flexible gas lines allows the package to be rotated a total of 200 degrees. The rotation motor is controlled from an EMI tight box next to the receiver that can be switched between local or remote operation.

The Input Signal Path

To achieve the maximum receiver sensitivity, it is essential to keep the attenuation in the signal path between the feed horn and the HEMT preamplifiers to an absolute minimum. For this reason a great deal of care was taken in designing the components in this waveguide and coaxial cable path.

Figure 3 shows that the first waveguide component is the calibration signal injection waveguide section. The waveguide section has a hole that accepts an insert whose inner surface maintains the waveguide's inner radius and has a rectangularly shaped vane suspended 1mm above the surface. Being terminated at one end with a 50 ohm resistor this vane behaves as a microstrip line and couples a fraction of the signal from a temperature controlled (40 +/- 0.1 degree C) noise source into the signal path. Positioned at 45 degrees to the orthomode transition output, a modulated noise source can be coupled equally into each polarization for the purpose of continuously monitoring each RF channel's system noise temperature and gain. By using a transfer switch and 10 dB coupler, two levels of noise calibration (~10 K and ~ 1 K) and a test tone are available. The next component in the input signal path is the vacuum barrier interface where the microwave signals enter the cryostat. This must maintain a high-quality vacuum seal to prevent the ingress of atmospheric contaminants whilst providing a low-loss microwave path. Kapton film, 0.125 mm thick, edge clamped over an O-ring face provides a suitable vacuum barrier, and an 85-mm-thick expanded polystyrene plug epoxied in place underneath the Kapton film provides mechanical support against atmospheric pressure. A slight taper in the waveguide at this point is used to reduce the chance of implosion.

The component that follows the vacuum window is the gapped waveguide structure. The primary task of this device is to stop heat flowing from the room-temperature vacuum window region (at ~300 K) to the orthomode transition (OMT) waveguide cooled to ~ 60 K. The gap separation in the waveguide wall-end faces is 1.0 mm and this separation is maintained by four G-10 fibreglass straps fixed securely to each side of the waveguide gap region. Each strap is 35 mm

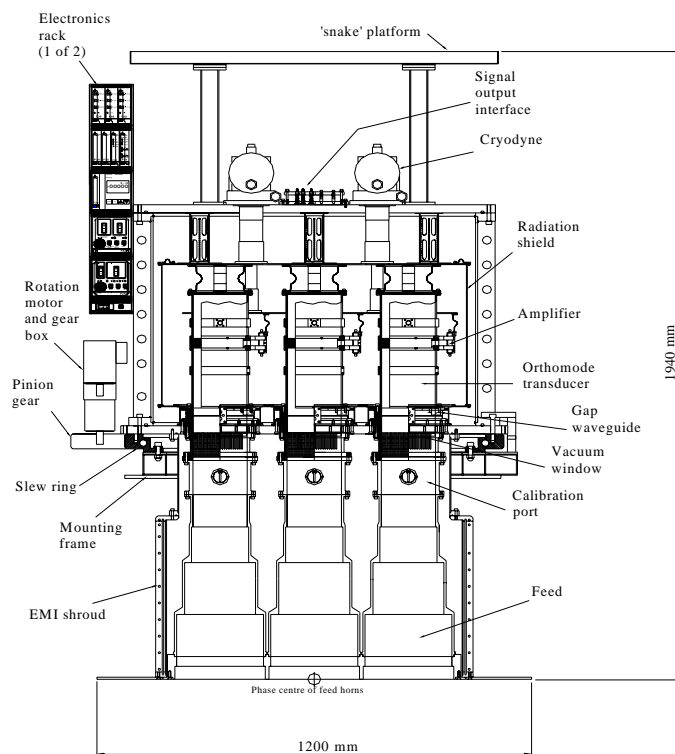


Fig. 3. Plan view of the assembled receiver



Fig. 4. Photograph of the assembled receiver with the cryostat wall removed to show the interior

wide, an insulation length of 32 mm and 1.7 mm thick, giving a total heat load around 0.67 W for each waveguide gap and 4.7 W for the full waveguide gap array. The conventional design for a gapped waveguide junction such as this would require a choke joint with a stub-like, quarter-wavelength groove, spaced one quarter wavelength from the waveguide walls, incorporated into the waveguide flange faces. For this system, however, because of the close proximity of the neighbouring waveguides, and also because of weight considerations, a simpler gap structure was adopted. The choke groove was eliminated, the gap spacing closed down to 1 mm and the flange face width set at 17.5 mm, making the series gap reactance less than 5 ohms at the operating frequency. When tested in the finished input-waveguide assembly, the effect of the gap on the overall match and insertion loss of the structure was minimal.

The final component in the input signal path is the waveguide-to-coaxial orthomode transition (OMT). This device uses simple orthogonal probes into waveguide structure to couple incoming signals from the input waveguide to the coaxial connectors on the outer waveguide walls. Short stainless-steel coaxial lines then connect these to the HEMT preamplifiers. It is important to note that the OMT is at a physical temperature of ~ 70 K, whilst the HEMT preamplifiers are operating at 12 K, and so a substantial temperature differential exists between the two, making it necessary to use stainless- steel coax lines for these connections. This form of OMT design was chosen because of its simplicity, ease of manufacture, and low insertion loss (< 0.04 dB for each probe).

Isolation between the orthogonal probes was achieved by separating the probes by about 0.1 guide wavelengths along the length of the guide. A septum is then used to tune the front probe; the rear probe is tuned by the waveguide backshort.

Extensive use was made of the Ansoft HFSS [5] simulation software to model the input waveguide as a single entity. It clearly showed the effect of the change in dielectric constant due to the vacuum window foam and led to the non-intuitive inclusion of a reduced diameter waveguide vacuum window. This manifests itself as a step in the waveguide wall – inwards at the feed end of the window and outwards at the OMT end. Final testing of the fully assembled horn-window-gap-OMT structure yielded an overall return loss of 20 dB across most of the operating band with only 15 dB achievable at the extreme lower end due to waveguide cutoff effects. Probe-to-probe isolation of 35dB was maintained.

The High Electron Mobility Transistor (HEMT) Amplifier

The amplifiers were manufactured in the ATNF laboratories. The design has been described in great detail by Gallego and Pospieszalski [6] and a view of the interior of one of the fabricated amplifiers is shown in Figure 5.

The design uses a hybrid MIC approach, with commercially available HEMT chips. FHR02X chips from Fujitsu are used for stages 1 and 2 and FSX017X chips for the higher 1 dB compression point, third stage. The change in chip selection for the third stage was prompted by the relatively high interference that exists in the vicinity of the Arecibo site. The chips are wire-bonded into microstrip matching and coupling networks realised in Duroid 6010.5, 0.050-inch-thick substrate material. The result is an amplifier with high gain (~ 37 dB), an input noise temperature of 5K across the operating band (1395 ± 150 MHz), low input and output reflection coefficients, and unconditional stability at any physical temperature in the range 5K to 300K.

The outputs from the 14 amplifiers are routed, for thermal isolation, by stainless steel cables to the cryostat lid where hermetic sub-miniature assembly (SMA) connectors are topped by a 'plug-in' plate with blind mate (BMA) connectors. This measure prevents damage to the cryostat hermetic connectors that would result in an inconvenient and prolonged repair procedure.

THE CRYOGENIC SYSTEM

The Vacuum Cryostat

Because of the diameter of the feed-horn array and the length of the cooled waveguide components contained within, the vacuum cryostat is required to have physical dimensions of 1.0 m diameter and 0.7 m long. This would not have been a difficult vacuum tank to construct if conventional stainless steel materials and techniques were used. A strict weight limit for the front end system imposed by the telescope Gregorian dome specifications precluded using stainless steel and so aluminium was used instead. Even then, the allowable weight of the cryostat and end plates required the use of relatively thin (6 mm) cryostat walls on the cylindrical section with stiffening bars welded on the outside to resist the hoop tension forces. The end plates were made from 25.4 mm stainless steel and required a set of four 25-mm-diameter support rods spaced around a 300-mm-diameter bolt circle around the centre of the tank to prevent the central region from deflecting excessively. This is an important requirement because the feed-horn must be kept in axial alignment when coupled to the cryostat input waveguide. To keep the gas pressure thermal load for this system well below 1 W requires the ultimate vacuum pressure within the cryostat, when operating at cryogenic temperatures, to be much less than 10^{-5} torr (preferably 10^{-6} torr). To assist in this activated charcoal traps have been installed on the 20-K platform to augment the cold metal surfaces in cryopumping leakage products. These perform best if regenerated at regular six-monthly intervals however we envisage the system will be used for a much longer period before any maintenance is undertaken.

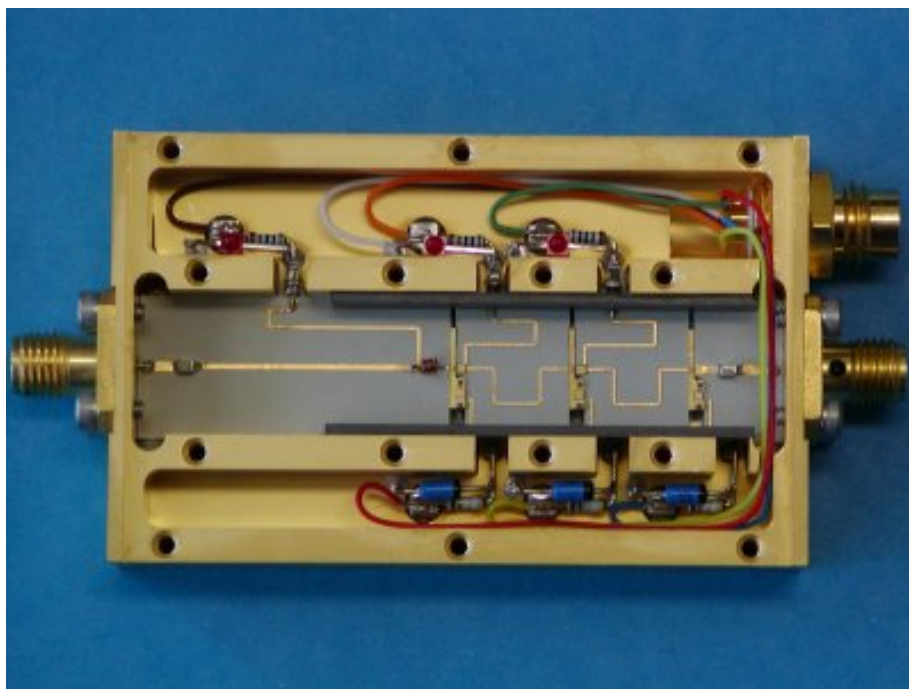


Fig. 5. An interior view of a 1200-1800 MHz HEMT amplifier.

The largest leakage component is known to come from the foam support plugs in the waveguide vacuum windows; this is because the gas used to generate the foam escapes to the high vacuum side. The speed of this process has been greatly increased (~50x) by drilling a matrix of holes in the foam so that the longest diffusion path for the escaping gas is now 2.5 mm.

Cryogenic Refrigerators

The cryogenic cooling for this system is provided by a pair of Cryogenic Technologies Inc (CTI) 1020 CP cryocoolers, operating in parallel and sharing the thermal load, with each operating from a separate helium compressor. The total capacity of this dual system should be 20 W on the 20-K platform and approximately 70 W on the 70-K platform. As is usual with these systems the 20-K platform is reserved for low-noise amplifier cooling whilst the 70-K platform is used to cool the radiation shields and, in this case, the 7 orthomode transitions. This arrangement can be seen clearly in Fig. 2. The calculated total equilibrium heat loads for all radiation, conduction and gas loads on both platforms are 40 W for the 70-K platform and 5 W for the 20-K platform. This agrees well with the CTI load-capacity curves, which indicate loads of 45 and 6 W for the observed platform temperatures.

The Parkes 13 beam receiver front end [1] made extensive use of super insulation between the radiation shields and the outer walls of the cryostat however it was calculated to be unnecessary for this receiver. Of note is the more general use of flexible printed circuit board (pcb) to carry control and monitoring signals between the cryostat hermetic connector and the 70-K stage plate rather than the more traditional cable loom. The reliability experienced and simplicity afforded

in assembly by printing the multi-pin connector pattern, that typically has 32 pins, on the flexible substrate has led to this technique being adopted for all new ATNF receivers.

The mass of metal attached to each platform amounts to 13 kg of copper at 20 K and 84 kg total of copper and aluminium at 70 K. The cooldown times for these enthalpy loads are 8 hours for the 20-K system and 36 hours for the 70-K system.

Cryodyne and rotation motor drives

The receiver rotation and cryodyne motor drive circuitry are contained in a single shielded box. This was a logical choice to satisfy NAIC's desire for low electromagnetic emission levels. The motor controller produces copious amounts of potential interference but this is mitigated with the filtering of all cables, extensive use of conductive fabric over foam to seal gaps and isolating the controller by housing it within another shielded box – a box within a box in effect. Cooling of the drive electrics was achieved using vents that take the form of a grid of holes in a metal block. The holes act as waveguides beyond cutoff for RF signals below a frequency of 30 GHz and this covers all frequencies likely to be used at Arecibo. The vent structure also provides substantial magnetic shielding.

SYSTEM PERFORMANCE SUMMARY

The completed receiver was tested in March 2004 and installed on the Arecibo telescope in late April 2004. The microwave and cryogenic performance is summarised in Table 1. Figure 6 shows the receiver noise temperature as measured using a hot load/sky temperature comparison. This noise temperature includes the feed array and calibration waveguide and interference from Sydney's city environment is obvious below 1.27 GHz and above 1.53 GHz. It is present to a lesser extent between these two frequencies yet the underlying low noise performance of the receiver can be seen to have been achieved. Figure 7 shows the feed pattern for one of the outer ring feeds and highlights the good agreement between modelled and measured data.

The receiver has been operating with good stability and sensitivity consistent with the overall system noise temperature and has also been used successfully outside the intended frequency band.

Other results are available on the NAIC ALFA web page - http://www.naic.edu/science/alfa_set.htm

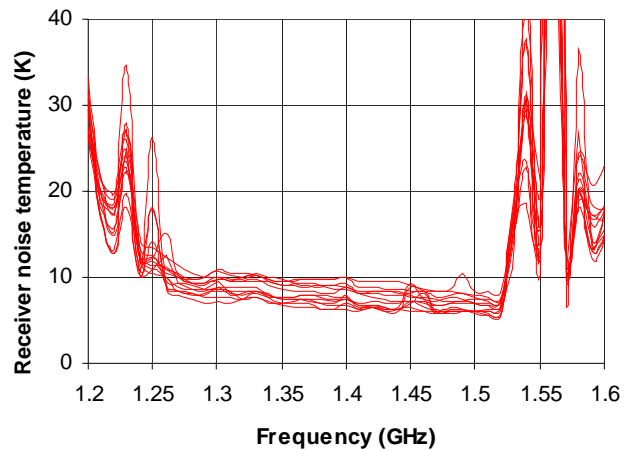


Fig 6. Spread of receiver noise temperature. All channels looking at the sky at the ATNFs Sydney site

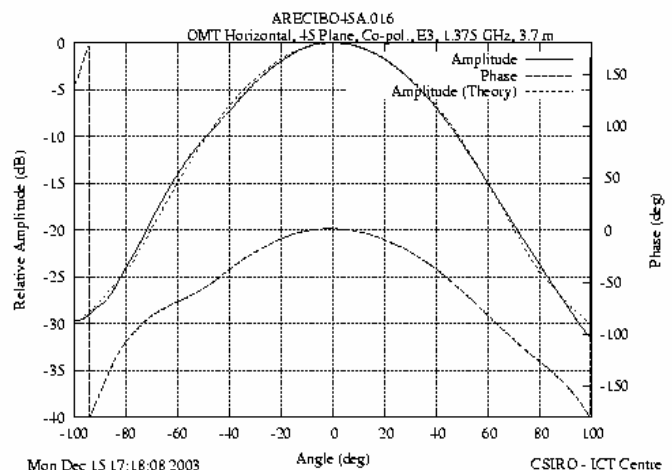


Fig 7. Predicted and measured radiation patterns for an outer ring feed.

Table 1. Summary of microwave and cryogenic performance

Operating Frequency:	1225 – 1525 MHz
Front end RF gain:	37 dB
Output spectral power density:	-62 dBm/MHz (cold sky)
Receiver noise temperature:	<10 K (measured at feed input)
Overall system noise temperature:	27 K (average of 14 receivers measured on telescope)
20 K platform temperature (HEMT amp):	12 K
70 K platform temperature:	60 K
Cooldown time: HEMT amplifiers:	8 hrs to 20 K 20 hrs to 12 K
Cooldown time: Radiation shields:	24 hrs to 70 K 44 hrs to 60 K
Mass cooled: 20 K platform:	13 kg
Mass cooled: 70 K platform:	84 kg

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