

## Specifications

### Standard Reference Instrument Series 6011

#### Josephson Arbitrary Waveform Synthesizer

**Description:** The Josephson arbitrary waveform synthesizer (JAWS) is an instrument that synthesizes ac voltage waveforms and dc voltages whose metrological accuracy results from pulse biasing thousands of series-connected superconducting Josephson junctions. The quantum accuracy of these voltages is derived from the Josephson Effect, such that every junction in the JAWS circuit produces the integer number and polarity of quantized voltage pulses at precisely determined time.

The JAWS system is essentially a digital-to-analog converter that generates time-dependent voltage signals that serve as a primary ac voltage standard. It is the only ac voltage standard source directly derived from quantum effects. Waveforms such as sine waves or arbitrary waveforms may be synthesized with frequencies and harmonics ranging from four hertz to a few megahertz frequencies. As a result of circuit and output lead impedances, the accuracy of the waveforms provided to test instruments will depend on the frequency, with lower audio frequencies having the lowest uncertainty. For example, a 1 kHz, 1 V rms sine wave has an uncertainty ( $k=1$ ) of one part in  $10^7$ , whereas a 100 kHz sine wave will have an uncertainty ( $k=1$ ) of one part in  $10^5$  at the output leads. The uncertainty is limited by ac leakage paths and is expected to decrease as more advanced measurement techniques are refined. System software characterizes and accounts for the largest of these errors. Contributions to the uncertainty include extrinsic effects such as transmission line errors, and quadrature errors from the compensation currents, as well as intrinsic errors from the delta-sigma code and phase noise. A detailed study is available on request.

Design, assembly and technical measurements leading to the production of this SRI were performed by P.D. Dresselhaus of the NIST Quantum Electromagnetics Division.

Support aspects involved in the issuance of this SRI were coordinated through the NIST Office of Reference Materials.

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**Specifications:** NIST provides the JAWS as Standard Reference Instrumentation (SRI) with performance that is equivalent to that of NIST systems in terms of quantum accuracy and precision measurement capability, provided that operators follow recommended best practices and perform intercomparisons with comparable quantum-based voltage sources. The NIST JAWS SRI is offered in a range of different configurations (SRI 6011d – SRI 6011i), from individual 2V JAWS cryo-packaged chips that contain the superconducting integrated circuit to fully integrated JAWS systems in which the chip is cooled by a cryocooler refrigerator to the operating temperature at which the JAWS circuit becomes superconducting. The JAWS chips are fabricated and packaged by NIST in accordance with existing and established fabrication protocols. All the system configurations of the JAWS SRI are constructed primarily from commercially available components and include software that optimizes the system performance and ensures that it produces quantum-accurate waveforms. The SRI6011i combines the SRI 6011f with the SRI 6000e (see <https://www.nist.gov/document/sri-6000> for the SRI 6000e specifications).

NIST researchers continue to develop and improve the JAWS systems and measurement techniques. The JAWS circuits and systems and associated measurement capabilities are identical to those of NIST systems at the time of acquisition. NIST is providing the JAWS through the SRI program with prices derived such that NIST is reimbursed for all costs associated with duplicating the current versions of NIST systems. Prices do not include support, training, warranty, or on-site installation and qualification. The customer should contact the Standard Reference Instrument office ([srminfo@nist.gov](mailto:srminfo@nist.gov)) for costs for these services.

The JAWS circuits and systems have the following specifications and features.<sup>1</sup>

- A) A cryopackaged chip that is tested and demonstrated to produce stable, quantum-accurate waveforms at up to 2 V rms with a minimum current range of 1.0 mA that is determined by a Total Harmonic Distortion better than -100 dBc.
- B) The capability to generate voltage waveforms with frequency components from 4 Hz up to 1 MHz.
- C) A majority of system components that are commercially available.
  - a. Fast pulse synthesizer operating at >12 Gpulses/s with at least two (2) independent channels
  - b. Isolated low-frequency waveform generators for bias with triggering
  - c. Wideband RF amplifiers with 30 dB gain, >30 GHz bandwidth, and >8 Vpp output
  - d. Low-noise digitizer with >50 MSa/s and >16-bit per sample for analysis and margins testing
- D) Patterns will use a pulse frequency of >12 Giga-pulses/sec with user-defined waveforms or a standard set of NIST-generated waveforms for standard voltages and frequencies: 0.1, 0.2, 0.5, 1, and 2 V rms at 100 Hz, 200 Hz, 500 Hz, 1 kHz, 2 kHz, 5 kHz, 10 kHz, 20 kHz, 50 kHz, and 100 kHz. Combined uncertainties ( $k=2$ ) in parts in  $10^6$  (220 mV range at 200 mV output voltage) are:

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<sup>1</sup> Certain commercial equipment, instruments or materials are identified in this certificate to adequately specify the experimental procedure. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

100 Hz	400 Hz	1 kHz	2 kHz	5 kHz	10 kHz	20 kHz
2	2	2	2	2	4	12

from Table 13, “Uncertainty analysis for ac–dc difference measurements with the AC Josephson voltage standard”, J. Underwood, *Metrologia* **56** 015012, 2019 (<https://doi.org/10.1088/1681-7575/aaf5e5>).

- E) Electronic and hardware integration components, cables, and equipment rack.
- F) A single-node license of the JAWS system software that automatically evaluates and optimizes the performance of the chip and the system electronics in order to ensure that the voltages are quantum accurate and have the largest current range.
- G) Application software that provides ac-dc difference measurements and calibrations of various voltage sources and meters

**Delivery:** Delivery and installation dates will be determined on a case-by-case basis in coordination with the customer and based on the availability of components and NIST staff.

**Shipping:** Unless otherwise agreed by the parties, shipping terms shall be [EXW \(Incoterms 2010\)](#). NIST will prepare packaging for shipment of the JAWS SRI. Shipping crate dimensions and weight will be included in each quote. Customers are responsible for arrangement of shipping pickup at NIST as well as all customs duties and import fees (HTC 9030.33.0040).

**Technical requirements at installation site:** Customers must provide the following:

- A) A 10 MHz reference signal whose frequency is accurate to a part in  $10^{10}$  or better.
- B) A Windows-based computer system (Windows 10 or higher) with at least 16 GB of RAM for data analysis and system operation. At least four (4) USB-2 ports are required.
- C) Customs related clearances, documents, payments, and fees.
- D) Appropriate power and utilities for compressors (for cryo-cooled systems only), including power and connectors for three-phase 208 V, 6 kW at 60 Hz (or three-phase 200 V, 5 kW at 50 Hz) power, and cooling water (for the water-cooled compressor only) and compressed air.
- E) As the customer deems necessary, the following additional instruments that are typically used for calibration measurements and are currently support by existing JAWS software:
  - a. A Fluke 792A thermal transfer standard
  - b. A Fluke 5790 ac voltmeter for rms voltage measurement

*Users of this SRI should ensure that the Specifications Certificate in their possession is current. This can be accomplished by contacting the Office of Reference Materials: telephone (301) 975-2200; e-mail [srminfo@nist.gov](mailto:srminfo@nist.gov); or via the Internet at <http://www.nist.gov/sri>.*

# Josephson Arbitrary Waveform Synthesizer (JAWS) System Configurations

## SRI 6011 series

### **6011d Cryo-packaged 2V rms JAWS chip (standalone)**

### **6011f Cryocooled 2V JAWS System (water-cooled compressor)**

- a. Fast pulse synthesizer operating at >12 Gpulses/s with at least two (2) independent channels
- b. Isolated low-frequency waveform generators for bias with triggering
- c. Wideband RF amplifiers with 30 dB gain, >30 GHz bandwidth, and >8 Vpp output
- d. Cryocooler with >400 mW cooling power at 4 K and water-cooled compressor
- e. Cryo-packaged 2 V rms JAWS chip
- f. Low-noise digitizer with >50 MSa/s and >16-bit per sample
- g. NIST JAWS software

### **6011g Cryocooled 2V JAWS System without fast pulse synthesizer (water-cooled compressor)**

- a. Isolated low-frequency waveform generators for bias with triggering
- b. Wideband RF amplifiers with 30 dB gain, >30 GHz bandwidth, and >8 Vpp output
- c. Cryocooler with >400 mW cooling power at 4 K and water-cooled compressor
- d. Cryo-packaged 2 V rms JAWS chip
- e. Low-noise digitizer with >50 MSa/s and >16-bit per sample
- f. NIST JAWS software

### **6011h Cryocooled 2V JAWS System (air-cooled compressor)**

- a. Fast pulse synthesizer operating at >12 Gpulses/s with at least two (2) independent channels
- b. Isolated low-frequency waveform generators for bias with triggering
- c. Wideband RF amplifiers with 30 dB gain, >30 GHz bandwidth, and >8 Vpp output
- d. Cryocooler with >400 mW cooling power at 4 K and air-cooled compressor
- e. Cryo-packaged 2 V rms JAWS chip
- f. Low-noise digitizer with >50 MSa/s and >16-bit per sample
- g. NIST JAWS software

### **6011i Cryocooled Combined 2V JAWS and 10V PJVS System (water-cooled compressor)**

- a. Fast pulse synthesizer operating at >12 Gpulses/s with at least two (2) independent channels
- b. Isolated low-frequency waveform generators for bias with triggering
- c. Wideband RF amplifiers with 30 dB gain, >30 GHz bandwidth, and >8 Vpp output
- d. Cryocooler with >400 mW cooling power at 4 K and water-cooled compressor
- e. Cryo-packaged 2 V rms JAWS chip
- f. Low-noise digitizer with >50 MSa/s and >16-bit per sample
- g. NIST JAWS software
- h. DS instrument SG22000PRO microwave synthesizer with frequency up to 22 GHz
- i. Cryopackaged 10V PJVS chip
- j. Mini-circuits ZVE-3W-183+ or DSI PA20000 or equivalent microwave amplifier
- k. Keysight 34420A nanovoltmeter
- l. NIST-designed JVS-701 dc current bias electronics with National Instruments: cDAQ-9178, NI 9403, 2 each NI 9264, NI 9238, GPIB-USB HS+, external computer and monitor