THE SUBMILLIMETER WAVE ASTRONOMY SATELLITE

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ABSTRACT

The Submillimeter Wave Astronomy Satellite (SWAS) was selected for development and flight by NASA in 1989 as one of the initial payloads in the Small Explorer program. SWAS is the first instrument designed to carry out submillimeter astronomical observations of spectral lines from space. Spectral lines of H_2, O_2, ^{13}CO, and atomic carbon, which are extremely difficult to observe from the ground but which are potentially important tracers of the structure of dense clouds in the interstellar medium, will be simultaneously observed with high spectral resolution. Incoming radiation is collected by a 55 x 71–cm offset Cassegrain antenna, with an aggregate surface error $\leq$ 9 μm rms. The receiver front end consists of two independent cooled Schottky diode harmonic mixers, each pumped by frequency–tripled phaselocked Gunn oscillator. Spectral analysis is performed on the 4 lines from the two mixers simultaneously by an acousto–optical spectrometer having a bandwidth of 1.4 GHz, and a frequency resolution of 1 MHz.

SWAS ANTENNA

We have chosen an offset Cassegrain design for its very low reflection coefficient and consequent low level of standing waves, which can cause undesirable baseline ripple in spectral line observations with a symmetric antenna. An elliptical aperture has been adopted to maximize the collecting area which can be accommodated within the the fairing of the Scout launch vehicle. The aperture dimensions of 55 x 71 cm result in beam size of 3.3' x 4.3' at a nominal operating frequency of 550 GHz. The antenna as well as the thermal radiators for the front end passive cooling (discussed below) are shielded from direct sunlight by a sunshade. The limited size of the sunshade results in relatively stringent restrictions on observations of any particular source. In fact the Earth, which obstructs a very large fraction of the sky from the low orbit altitude of $\cong$ 500 km, must also be avoided to obtain good thermal stability.

We have developed a relatively stringent specification for the surface accuracy. The 9 μm rms error, which corresponds to $\lambda/60$ rms, is required to achieve a relatively high aperture efficiency ($\epsilon_{ruze} = 0.96$). Currently the most promising material for the fabrication of primary and secondary mirrors is a silicon carbide, which combines low weight and high stiffness with good thermal properties, and can be polished to the required surface accuracy. The surface will be metallized to ensure high reflectivity in the submillimeter region, and will probably be painted to enhance its thermal properties.

The primary focal ratio is $f/D \simeq 0.25$, and the secondary focal ratios are 3.3 and 4.3 for the two principal axes. The molecular clouds that will be SWAS's targets are extended on size scales up to $\simeq 1^o$ in tracers that have been observed from the Earth's surface. These clouds are grouped into complexes, and these complexes are heavily concentrated towards the plane of the Galaxy. Consequently, finding a region free of emission is highly problematic; this fact, together with the relatively fast primary, precludes nutating the secondary mirror to move the antenna beam on the sky so as to serve as an input Dicke switch. We have adopted the approach of ***moving the entire antenna and receiver front end as a unit***, relative to the spacecraft. This will be carried out by means of a two–axis gimbal system, shown in Figure 1, which permits motions up to $\pm 3^o$ in any direction relative to the nominal spacecraft pointing direction. The antenna motion is controlled by a pair of ball screws operated by stepping motors. The IF signals are carried over the pivots by means of cable wraps made of several turns of semi–rigid cable.

RADIOMETER FRONT END

Submillimeter radiometers are still relatively less developed than their counterparts at longer wavelengths. One of the major impediments is the lack of local oscillators which can meet the requirements for space missions of reliability, low mass, and very limited power consumption. These considerations eliminate submillimeter lasers and vacuum tube oscillators from consideration for a small payload such as SWAS. A harmonic mixer having a single diode pumped at approximately 1/2 the input frequency is used in the SWAS front end. This design has been refined considerably during the past few years, and the simplicity of its design makes it suitable these small wavelengths.

SWAS Dual Receivers

As shown in the system block diagram presented as Figure 2, the SWAS front end consists essentially of two independent receivers. The low frequency channel, designed to study emission from molecular oxygen (f = 487.25 GHz) and neutral carbon (f = 492.16 GHz) has a 81.6 GHz Gunn oscillator which is frequency tripled to provide a pump for the harmonic mixer at approximately 246 GHz. The high frequency channel follows a similar plan, but with the Gunn oscillator near 92 GHz. This Gunn oscillator can be electrically tuned to also cover the isotopically substituted variant of water vapor, $H_2{}^{18}O$, at 547.6 GHz.

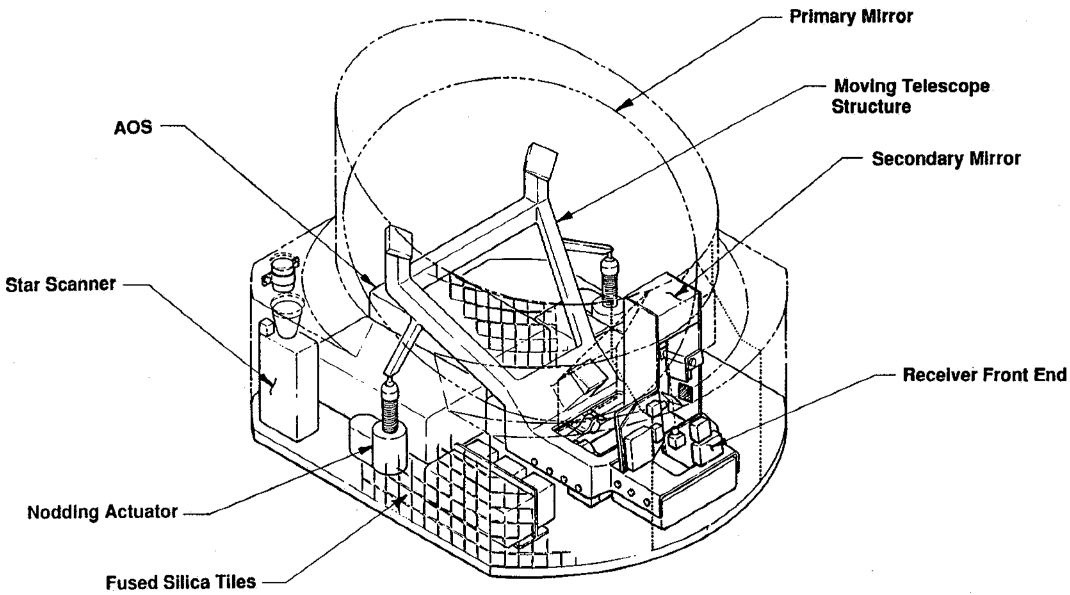

Figure 1. – Cutaway schematic view of SWAS instrument showing major subsystems.

Input Optics

The radiation from the antenna is coupled to the harmonic mixers by smooth–walled conical feedhorns. There is a highly desirable agreement between the elliptical aperture of the SWAS antenna and the asymmetry of radiation pattern of this type of feedhorn. Optimization of the feedhorn aperture and slant length results in a predicted aperture efficiency > 0.80 overall for the antenna. This is obtained even with the constraint of relatively high > 13 dB edge taper designed to (1) minimize spillover which could cause baseline problems and (2) enhance the beam efficiency which is relevant for study of extended sources. The two receivers operate in orthogonal linear polarizations referred to the antenna, and they are diplexed by a wire grid polarizer. In order to preserve the correct asymmetry of the conical feedhorn patterns relative to the SWAS elliptical aperture the signal to one of the receivers is processed by 90 degree polarization rotator—it has the effect of rotating the polarization while leaving the beam asymmetry unaffected.

Cooling and System Performance

The input polarizing grid, feedhorns, harmonic mixers, triplers, and first IF amplifiers are rigidly mounted together at the Cassegrain focus of the antenna. These front end components are cooled by passive thermal radiators to a temperature between 120 K and 150 K. (Note that the Gunn oscillators and other millimeter wavelength components are rigidly coupled to triplers and harmonic mixers, but are not cooled). Cooling the Schottky diode mixers has the well–known effects of reducing their noise and required local oscillator power. The triplers are cooled to eliminate the high loss that would result from the long run of waveguide required if they were at ambient temperature, but had still to be connected to the cooled harmonic mixers. Cooling produces a major reduction in the noise of the IF amplifiers which, however, make a relatively small contribution to the overall system noise.

The noise temperature of the SWAS receivers, based on measurements of a prototype currently under test as well as of other radiometers of similar design should be nearly linearly dependent on physical temperature for temperatures down to 100 K. Operation at a temperature of 150 K should result in a double sideband system noise temperature of 1250 K. Since the SWAS radiometers are used for spectral line observations, but as no sideband selection is possible since we wish to observe lines in both sidebands simultaneously, the relevant noise temperature is 2500 K (SSB). Including a factor of two for switching, the minimum detectable temperature difference for 1200 s. integration and 1 MHz bandwidth is 0.14 K rms.

Calibration

Calibration of the radiometer systems is vitally important for obtaining useful astronomical data. The spectroscopic data from the SWAS radiometers will be obtained by taking the difference between outputs viewing the "source" and the "reference" positions, separated on the sky by up to a few degrees. Following the practice widely used at millimeter wavelengths, the quantity [((source) – (reference))/(reference)] · T_{sys} is formed from the outputs of each channel of the spectrometer to correct for the gain of each spectral channel. T_{sys} is the system temperature which must be measured separately. The system temperature is obtained by assuming that the antenna temperature when observing the reference position is zero, and using this measurement together with observations of an internal calibration load. The temperature of this load is not critical, as long as it is accurately known from thermometers. The calibration load is coupled to the receivers by a mechanically operated mirror. From

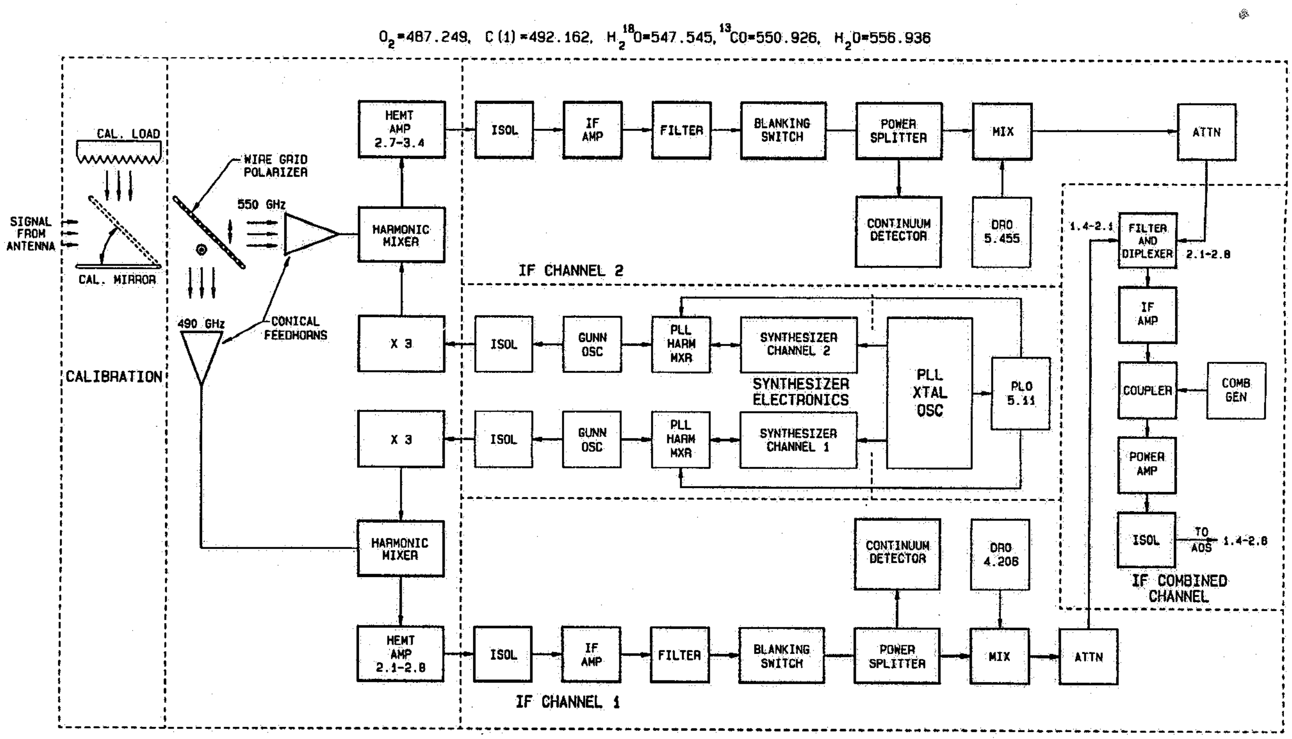

Figure 2. – Block diagram of SWAS submillimeter front end and IF system components

thermal considerations, the calibration load is expected to be near ambient temperature (≅ 250 K). The antenna temperature change between reference and calibration load is approximately 20 % of the double sideband system temperature, and should thus not be a problem in terms of system nonlinearity. Additional calibration of the system, including the antenna performance, will be obtained by observations of Jupiter, which appears as a point source to the SWAS antenna beam.

Frequency Control

To carry out spectral line observations, the operating frequency of the SWAS radiometers must be known and controlled to a fraction of the spectral resolution of 1 MHz. As seen in Figure 2, the Gunn oscillators for both channels are phaselocked to a harmonic of a 5.11 GHz reference oscillator, which in turn is locked to a 10 MHz ovenized crystal oscillator. Frequency adjustments of the Gunn oscillators to compensate for Doppler shifts of the astronomical source and those produced by the motion of the spacecraft are made in the phaselock loops by changing the reference frequencies, which are actually the synthesizers shown in the middle of the receiver block diagram. To minimize problems with the loop performance and reduce the number of control bits required, the frequency is adjusted in steps of 2 MHz. As each spectral line can use up to 350 MHz of the spectrometer, this coarseness of control should not compromise performance. The frequency change during a single observation of a source due to changing projections of velocity vectors will considerably exceed the width of a single channel. The data will be recorded in separate 2 second segments which during data reduction will be shifted in frequency as required to correct for this effect. The local oscillator frequencies for observations of a particular source during a given orbit will thus be left fixed.

IF SYSTEM

The IF bands are 2.7 – 3.4 GHz for the high frequency SWAS channel, and 2.1 – 2.8 GHz for the low frequency channel. As shown in Figure 2, each has a cooled HEMT amplifier, which has sufficient gain to set the IF system noise temperature. As the connection between each HEMT amplifier and the following stage must accommodate flexing due to antenna motion, particular care must be taken to ensure very low VSWR at this point. Each channel has a broadband continuum detector for measurements of planets, which form part of the calibration procedure. The continuum level detectors will also be valuable for monitoring system performance. A second down conversion is carried out by a mixer pumped by a dielectric resonator oscillator. The two channels are combined into a single path by a diplexer having an output frequency range of 1.4 to 2.8 GHz, which is the input bandpass of the acousto–optical (AOS) spectrometer. Preceding the AOS is a power amplifier which provides the required drive level, and which is carefully selected to have extremely good linearity over the necessary power range.

SPECTROMETER

The acousto–optical spectrometer provides the spectral analysis capability critical for the astronomical observations to be carried out by SWAS. This type of spectrometer yields a very large number of resolution elements covering a very wide bandwidth, combined with low power consumption and low mass. The AOS to be used is based on a number of units which have been used very successfully for radio astronomy in the millimeter wavelength range. The modifications for SWAS include increasing the bandwidth by use of a new Bragg diffraction cell, made of lithium niobate. The 1.4 GHz bandwidth allows simultaneous observation of 4 spectral lines. Redundant laser diodes and CCD arrays will be implemented to reduce likelihood of single point failures. The total power consumption of the AOS, including the electronics which digitize and integrate the output for periods of 2 seconds, is approximately 15 watts.

OPERATION AND OBSERVATIONS

The overall mass of SWAS, including the spacecraft and the instrument, is approximately 200 kg, and to have a minimum two year mission lifetime requires an initial perigee of at least 530 km. The orbit of SWAS has not been definitively determined, and it may be either an equatorial or a 38 degree inclined orbit, depending on the capability of available launch vehicles. Once launched, the passively–cooled front end components will take some time to reach their steady state temperature, during which period a variety of system tests will be carried out. Following this, scientific observations will be carried out almost continuously. As the system has no expendables, its lifetime will likely be limited by orbital decay, with a minimum expected duration of 2 years.

Observing a source will start with acquisition of guide stars by an optical star tracker which is co–boresighted with the submillimeter beams. The pointing accuracy is specified to be better than 1/5 beam width rms. The data taking will begin with a receiver calibration scan, followed by a sequence of position–switched observations. Since the abundance and hence the line intensities of H_2O and O_2 in the interstellar medium are not known, it is difficult to precisely define the integration time per position that will be used. A variety of mission scenarios have been developed based on different adopted abundances for these species.

The minimum successful mission will consist of three parts. The first is to gain an understanding of the abundance of the potentially very important molecules water and oxygen in a representative selection of sources within 1 kpc (3000 light years) of the sun. The second is to carry out a "mini–survey" of a large number of giant molecular clouds spread throughout the Milky Way to gain a Galaxy–wide picture of the distribution of molecular oxygen and atomic carbon, together with water and ^{13}CO where possible. The third part is to make relatively complete maps of a number of nearby clouds to determine how the abundance of these species varies as a function of position within these regions. There are many extensions to the mission which will be carried out if the astrophysics and technology permit, including making a complete survey of clouds in the Milky Way, obtaining maps with enhanced angular resolution, and studying other galaxies.

The SWAS mission is intended to open up the submillimeter region for high resolution astronomical spectroscopy. This wavelength region is exploited only with great difficulty from the surface of the Earth, and the advent of submillimeter technology suitable for space missions should permit a vast new range of important observations. The results of a successful SWAS mission should greatly improve our knowledge of chemistry in interstellar space. We expect that SWAS will significantly enhance our understanding of the structure of molecular clouds, and increase our information about how new stars are formed in these objects. At the present time, SWAS is scheduled for launch in June 1995.

We are pleased to acknowledge the important contributions of many individuals at NASA Goddard Spaceflight Center, Harvard–Smithsonian Center for Astrophysics, Ball Aerospace Systems Group, and Millitech Corporation to the SWAS project, which cannot be specifically enumerated.