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GALAXY EVOLUTION AT HIGH-REDSHIFT: MILLIMETER-WAVELENGTH SURVEYS WITH THE AZTEC CAMERA

A Dissertation Presented
by
KIMBERLY S. SCOTT

Submitted to the Graduate School of the University of Massachusetts Amherst in partial fulfillment of the requirements for the degree of DOCTOR OF PHILOSOPHY

September 2009

Department of Astronomy
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KIMBERLY S. SCOTT

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To my always supportive parents Ron and Brenda and my loving husband Dan.
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I would like to deeply thank my adviser, Grant Wilson, for his unfailing support. His positive attitude and encouragement have given me the strength and confidence to push ahead even in the toughest times, and I am eternally grateful for all that he has taught me over these past six years.

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I am grateful to my parents Ron and Brenda Scott for their love and for supporting me in everything I do. And finally, I thank my husband Dan Cavanaugh for his love, patience, and ability to keep me smiling.
Galaxies detected by their thermal dust emission at submillimeter (submm) and millimeter (mm) wavelengths comprise a population of massive, intensely star-forming systems in the early Universe. These “submm/mm-galaxies”, or SMGs, likely represent an important phase in the assembly and/or evolution of massive galaxies and are thought to be the progenitors of massive elliptical galaxies. While their projected number density as a function of source brightness provides key constraints on models of galaxy evolution, SMG surveys carried out over the past twelve years with the first generation of submm/mm-wavelength cameras have not imaged a large enough area to sufficient depths to provide the statistical power needed to discriminate between competing galaxy evolution scenarios. In this dissertation, we present the results from SMG surveys carried out over the past four years using the new sensitive mm-wavelength camera AzTEC. With the improved mapping speed of the AzTEC camera...
combined with dedicated telescope time devoted to deep, large-area extragalactic surveys, we have tripled both the area surveyed towards blank-fields (that is, regions with no known galaxy over-densities) at submm/mm wavelengths and the total number of detected SMGs. Here, we describe the properties and performance of the AzTEC instrument while operating on the James Clerk Maxwell Telescope (JCMT) and the Atacama Submillimeter Telescope Experiment (ASTE). We then present the results from two of the blank-field regions imaged with AzTEC: the JCMT/COSMOS field, which we discovered is over-dense in the number of very bright SMGs, and the ASTE survey of the Great Observatories Origins Deep-South field, which represents one of the deepest surveys ever carried out at submm/mm wavelengths. Finally, we combine the results from all of the blank-fields imaged with AzTEC while operating on the JCMT and the ASTE to calculate the most accurate measurements to date of the SMG number counts.
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CHAPTER 1

MILLIMETER-SELECTED GALAXIES AND THEIR ROLE IN GALAXY EVOLUTION

Understanding how the arrangement of matter in the Universe evolved from a nearly homogeneous distribution as traced by the cosmic microwave background radiation into the stars, galaxies and large-scale structure observed today is a major goal of observational cosmology. Significant improvements in astronomical instrumentation and telescope design over the past few decades have greatly improved the sensitivity and quality of observations at all wavelengths, resulting in the detections of thousands of galaxies in the early Universe. Combined with revolutions in our understanding of gravitational processes in the paradigm of general relativity, we seek a coherent picture of how structure forms and evolves by addressing a few fundamental questions:

- What physical processes control the assembly of the earliest galaxies and their evolution into the types of galaxies that we see in the local Universe?

- In what systems is the bulk of star-formation taking place, and how does this evolve with cosmic time?

- How are massive galaxies related to the formation and growth of super-massive black-holes?

- How does galaxy formation depend on the surrounding large-scale environment?

Galaxies in the local Universe are generally classified by their stellar morphologies and divided roughly into three groups: those with well-defined spiral structure
mostly confined to a disk ("disk-galaxies"); spheroidal galaxies with smooth stellar density profiles ("elliptical galaxies"); and those with no obvious structural organization ("irregular galaxies") (Hubble, 1926; de Vaucouleurs, 1959). Disk-galaxies typically contain a mix of young and old stars and are actively forming stars at modest rates ($\sim 1 \, M_\odot/\text{yr}$) from large reservoirs of cold gas. On the other hand, elliptical galaxies are more massive (with stellar masses of $10^9-12 \, M_\odot$), consist primarily of old stars, and are relatively devoid of gas and consequently have little ongoing star-formation (see reviews by Roberts, 1963; van den Bergh, 1975; Roberts & Haynes, 1994; Renzini, 2006). To account for the population of old stars in massive ellipticals, their major phase of star-formation must have occurred at early epochs and may have proceeded very efficiently during their early history.

It has long been debated whether disk-galaxies and elliptical galaxies are connected through an evolutionary sequence. In the standard cosmology model, small density perturbations in the early Universe which are traced by the cosmic microwave background radiation (CMB; Penzias & Wilson, 1965; Smoot et al., 1992; Hinshaw et al., 2009) grow as slow-moving cold dark matter particles (e.g. Peebles, 1982) clump together and collect on a variety of mass scales (see review by Narlikar & Padmanabhan, 2001). In this paradigm galaxies are assembled from these initial fluctuations through the influence of gravity in a hierarchical, or “bottom-up” manner, since the largest density fluctuations in the matter distribution occur on the smallest mass scales (Larson, 1969; Press & Schechter, 1974). This hierarchical formation model supports an evolutionary scenario in which massive elliptical galaxies are formed from the mergers of less massive disk-galaxies. The merging of two gas-rich disk-galaxies can also trigger intense star-formation (e.g. Barnes & Hernquist, 1991, 1992; Genzel et al., 1998) that could build up the massive stellar population observed in local elliptical galaxies.
Due to the finite speed of light, observations of increasingly distant galaxies give us a glimpse further and further into the past and enable a direct study of how the properties of galaxies change over cosmic time. Light emitted from a distant galaxy is also increasingly redshifted to longer wavelengths with increasing distance due to the expansion of the Universe. We therefore parametrize the epoch at which we observe a given galaxy by its redshift $z$, where $1 + z = \frac{\lambda_{\text{obs}}}{\lambda_{\text{rest}}}$, $\lambda_{\text{obs}}$ is the observed wavelength, and $\lambda_{\text{rest}}$ is the wavelength of the light in the rest-frame of the galaxy. For reference, the light detected from a galaxy at $z = 1.5$ was emitted when the Universe was roughly half its current age.

We trace the formation history of galaxies primarily through the evolution of their star-formation activity. Young star-forming galaxies are bright at ultra-violet (UV) wavelengths due to thermal emission from the large number of hot, short-lived massive stars. For galaxies at $z > 2.5$, this emission is redshifted into optical wavelengths. In the past decade, the sensitivity afforded by 8-m class telescopes has resulted in the detection of a large number of young star-forming galaxies at $z \gtrsim 2$ in deep optical surveys. These include Lyman-break galaxies (LBGs; e.g. Steidel et al., 1996; Giavalisco et al., 1996; Madau et al., 1996) and $BzK$-selected galaxies (Daddi et al., 2004) identified through multi-band photometry and Lyman-α emitting galaxies (LAEs; e.g. Hu & McMahon, 1996; Cowie & Hu, 1998; Hu et al., 1998), which exhibit strong emission lines from the ionization and subsequent recombination of hydrogen. The most distant galaxy detected to date is at $z = 6.96$ (Iye et al., 2006), when the Universe was less than one billion years old (roughly 10% of its current age). These galaxies have moderate star-formation rates of SFR $\approx 10 - 100$ M$_\odot$/yr (Giavalisco, 2002), consistent with expectations from merger-triggered starbursts in the paradigm of hierarchical galaxy formation (Cole et al., 1994; Baugh et al., 1998). Large surveys of these high-redshift galaxies have revealed that a broad peak of star-formation activity in the Universe occurred between $1 < z < 2$ (e.g. Lilly et al., 1996; Connolly
Figure 1.1. The average star-formation rate density in the Universe as a function of redshift. The red data-points are determined from surveys of optical/UV-selected galaxies without including a correction for dust-extinction: triangles – Lilly et al. (1996); squares – Connolly et al. (1997); crosses – Steidel et al. (1999); circles – Giavalisco et al. (2004b). The blue data-points with the same symbols represent the values after a correction for dust-obscuration (Adelberger & Steidel, 2000). The blue dashed curve is from optical/UV-selected galaxies from the Keck Deep Fields survey (Sawicki & Thompson, 2005, 2006a) and includes a correction for dust-extinction (Sawicki & Thompson, 2006b). The black curves show the contribution to the star-formation history from submm-selected galaxies: solid curve – Chapman et al. (2005); dot-dashed curve – Aretxaga et al. (2007); dashed curve – Dye et al. (2008). This Figure was adapted from Giavalisco et al. (2004b) and Dye et al. (2008).

et al., 1997; Steidel et al., 1999; Giavalisco et al., 2004b; Hu et al., 2004; Sawicki & Thompson, 2006b). This is demonstrated in Figure 1.1, where the red data-points show the average SFR per co-moving volume in the Universe as a function of redshift (Madau et al., 1996). The steep decline in star-formation activity since $z < 1$ has been well-established.

However, these high-redshift optical/UV-selected galaxies are unable to account for the massive, evolved stellar populations found in $z < 1$ elliptical galaxies (e.g. Jimenez et al., 2007) which have essentially been passively evolving since that epoch (Brinchmann & Ellis, 2000; McCarthy et al., 2001; Cimatti et al., 2002), suggesting
that they must have formed with significantly higher SFRs than those measured in LBGs and LAEs. However, it is known that star-formation takes place within dense molecular clouds which contain large amounts of dust, and this dust absorbs the optical/UV light emitted from nearby star-forming regions. Therefore a significant fraction of ongoing star-formation in galaxies can be heavily obscured by dust and will remain undetected in even the deepest optical surveys. The dust grains are heated by the starlight and thermally re-radiate this energy at far-infrared (FIR) to millimeter (mm) wavelengths, with the peak of dust emission occurring at $\lambda \approx 60-100 \, \mu m$ (Soifer & Neugebauer, 1991). In 1983, the Infrared Astronomical Satellite (IRAS) completed an all-sky survey at mid-IR to FIR wavelengths ($\lambda = 12-100 \, \mu m$), revealing the obscured star-formation from $\approx 20,000$ previously unknown galaxies at $z \lesssim 0.6$ (Saunders et al., 1990) and discovering a population of extremely luminous galaxies with bolometric luminosities of $L_{\text{FIR}} > 10^{12} \, L_\odot$ that emit the bulk of their emission at FIR wavelengths due to large amounts of dust (see review by Soifer et al., 1987). These ultra-luminous infrared galaxies (ULIRGs, see review by Sanders & Mirabel, 1996) represent the most violent mergers of gas-rich disk-galaxies observed in the local Universe and are proposed to evolve into massive elliptical galaxies through merger-induced dissipative collapse (Kormendy & Sanders, 1992).

The Cosmic Background Explorer (COBE), which mapped the sky at FIR–mm wavelengths, provided the first detection of the cosmic infrared background (CIB), which is the total integrated IR light emitted from all galaxies throughout the history of the Universe (Puget et al., 1996; Hauser et al., 1998; Fixsen et al., 1998). As shown in Figure 1.2 the energy density contained in the CIB is roughly equal to that in the optical background (Bernstein et al., 2002a,b), indicating that half of the star-formation activity in the Universe is obscured by dust. The galaxies detected in the local Universe by IRAS and at optical/UV wavelengths at high-redshift cannot account for all of the energy density in the CIB, indicating the existence of a sig-
nificant population of dusty, high-redshift galaxies. Obtaining a full understanding of galaxy formation and evolution thus requires studies of the dust-obscured high-redshift Universe.

Innovations in detector technology in the mid-1990’s provided the first astronomical cameras at submm/mm wavelengths and the first glimpse at dust-obscured star-formation activity in the early Universe. A population of high-redshift, extremely dust-obscured galaxies was revealed a decade ago (Smail et al., 1997; Hughes et al., 1998; Barger et al., 1998) with the Submillimeter Common User Bolometer Array (SCUBA) camera operating at 850 µm on the 15-m James Clerk Maxwell Telescope (JCMT, Holland et al., 1999). Observations at submm/mm wavelengths sample the Rayleigh-Jeans tail of the thermal dust spectrum, which rises steeply with frequency as $I_\nu \propto \nu^{2+\beta}$, where $\beta = 1.5 - 2.0$ (Dunne et al., 2000) and is the dust emissivity spectral index. The rest-frame IR to radio spectral energy distribution (SED) as a function of frequency for a $L_{\text{FIR}} = 10^{13} L_\odot$ ULIRG is shown in Figure 1.3 as an example. For observations at $\lambda > 500$ µm, the climb up this steep spectrum with increasing redshift roughly cancels the effect of cosmological dimming with increasing distance (e.g. Blain et al., 2002). Figure 1.4 shows how the measured flux density of a typical ULIRG with a given bolometric luminosity depends on its redshift at various observed wavelengths, demonstrating how galaxies selected at submm/mm wavelengths are equally detectable between $1 < z < 10$ (assuming that a sufficient amount of dust is already in place at such early epochs). This effect makes submm/mm wavelengths ideal for studying obscured star-formation during the epochs at which galaxies first started to form. Since the SFR of a galaxy is directly proportional to its FIR luminosity (Kennicutt, 1998), a flux-limited survey at submm/mm wavelengths is equivalent to a SFR-limited survey for $1 < z < 10$.

Surveys aimed at detecting a statistically significant number of submm/mm-selected galaxies (referred to hereafter as SMGs) have been carried out over the
Figure 1.2. The energy density in the extragalactic background light as a function of wavelength. The filled circles with error bars in the optical/near-IR are from Bernstein et al. (2002a), Wright & Reese (2000), Gorjian et al. (2000), and Wright (2001). The open circles and heavy line at FIR-mm wavelengths indicate detections of the CIB from COBE (Puget et al., 1996; Fixsen et al., 1998). Lower limits at all wavelengths are determined from the integrated flux in detected sources (Armand et al., 1994; Williams, 1996; Gardner et al., 1997; Hacking & Soifer, 1991; Blain et al., 1999). Upper limits are from Hurwitz et al. (1991, 1600 Å) and Hauser et al. (1998). The lines indicate various models of the extragalactic background light from Fall et al. (1996, FCP96), Malkan & Stecker (1998, MS98), and Dwek et al. (1998, D98). This Figure was reproduced from Bernstein et al. (2002b); refer to that paper for more details of the data and models presented here.
Figure 1.3. The spectral energy distribution (SED) for a typical $L_{\text{FIR}} = 10^{13} \ L_\odot$ ultra-luminous infrared galaxy. The three black curves show the same SED redshifted to $z = 1$, 2, and 5. The red and blue vertical bars indicate the bandpasses for 850 $\mu$m- and 1.1 mm-wavelength cameras, respectively, demonstrating how observations at these wavelengths can detect a galaxy of a given bolometric luminosity in a flux-limited survey nearly independent of redshift. Figure courtesy of M. Yun.
Figure 1.4. The measured flux density for a typical ultra-luminous infrared galaxy as a function of redshift for wavelengths $\lambda = 24 \, \mu m - 2.1 \, mm$. The two black curves show the redshift dependence at optical and radio (1.4 GHz) wavelengths. Figure reproduced from Blain et al. (2002).
past twelve years. While the first maps with SCUBA at 850 µm were limited in size (< 100 arcmin²; Smail et al., 1997, 2002; Hughes et al., 1998; Barger et al., 1998, 1999; Blain et al., 1999; Eales et al., 1999, 2000; Cowie et al., 2002; Chapman et al., 2002; Serjeant et al., 2003; Webb et al., 2003) due to the small field-of-view and limited sensitivity of the instrument, focus in the past five years has been on deep, wide-area surveys of “blank-fields”, i.e. regions of sky with no known biases in galaxy density, in order to amass large catalogs of bright SMGs for subsequent multi-wavelength follow-up and to study the global properties of this population (Scott et al., 2002; Borys et al., 2003; Wang et al., 2004; Mortier et al., 2005). In addition to SCUBA, the MAMBO camera (1.2 mm; Kreysa et al., 1998) on the Institut de Radio Astronomie Millimétrique (IRAM) 30-m telescope and Bolocam (1.1 mm; Glenn et al., 1998; Haig et al., 2004) on the 10-m Caltech Submillimeter Observatory (CSO) have been used for wide-area SMG surveys at mm wavelengths (Greve et al., 2004, 2008; Laurent et al., 2005; Bertoldi et al., 2007). Collectively, these projects have imaged ∼ 0.5 deg² of sky to depths of 1σ = 0.5 – 3.5 mJy (all scaled to 1.1 mm) and have detected ∼ 300 bright SMGs in blank-field surveys. Several small-area maps towards biased environments, such as massive galaxy clusters and proto-clusters at high-redshift, have also been carried out (Smail et al., 1997, 2002, 2003; Blain et al., 1999; Ivison et al., 2000; Chapman et al., 2002; Cowie et al., 2002; Knudsen et al., 2006, 2008; Greve et al., 2007).

Assuming that star-formation activity is the dominant heating source of the dust, the FIR luminosities of SMGs ($L_{\text{FIR}} \sim 3 \times 10^{12} - 10^{13} L_\odot$) imply SFRs $\sim 1000 M_\odot/yr$, leading many to suggest that they are scaled-up, high-redshift analogs to the local ULIRG population detected by IRAS (Blain et al., 2002). However, their number density is much higher than that expected from galaxies whose luminosity does not evolve with time (e.g. Blain et al., 1999; Guiderdoni et al., 1998), suggesting strong evolution in the luminosity function. The cumulative number density of SMGs as a
function of source flux density determined from several 850 µm surveys taken with SCUBA is shown in Figure 1.5. The long-dashed curve in the lower left corner of the plot indicates the expected number density of sources assuming no evolution in the luminosity function, which severely under-predicts the observed SMG counts by a factor of $\approx 1000$. SMGs must therefore represent a population of high-redshift galaxies undergoing an important starbursting phase in their evolution. Given their high SFRs, they are capable of forming all of the stars in a massive galaxy within $\sim 1$ Gyr, suggesting that SMGs may be the progenitors of the massive elliptical population observed in the local Universe.

This evolutionary path is indirectly supported by results from multi-wavelength follow-up of SMGs, which is essential in order to determine the nature of these sources. Spectroscopic redshifts for a sample of 73 radio-detected SMGs have revealed a median redshift of 2.2 (with an inter-quartile range of $1.7 - 2.8$) for this population (Chapman et al., 2005) and that their co-moving number density is consistent with that of present-day elliptical galaxies. SMGs also contain sufficient reservoirs of cold molecular gas ($10^{10-11} M_\odot$) needed to form the large populations of stars in elliptical galaxies. Their carbon monoxide (CO) gas kinematics often show complex, disturbed gas motions consistent with expectations from short-lived starbursts in mergers of gas-rich galaxies (e.g. Tacconi et al., 2008). Several of the brightest SMGs also have multiple radio counterparts separated by $2 - 6''$, or $20 - 50$ kpc at $z \sim 2$, or appear extended in their radio imaging (e.g. Chapman et al., 2004; Ivison et al., 2007; Biggs & Ivison, 2008), consistent with the separations expected for early starbursts in merging systems.

SMGs may contribute significantly ($10-20\%$) to the cosmic star-formation activity at $z \gtrsim 2$. The black curves in Figure 1.1 show estimates of the SFR density as a function of redshift from the SMG population (Chapman et al., 2005; Aretxaga et al., 2007; Dye et al., 2008). For comparison, the contribution from optical/UV-selected
Figure 1.5. The cumulative number density of 850 µm-selected sources as a function of flux density. The SHADES data (filled circles and best-fit curves) are from Coppin et al. (2006). Other symbols represent the number counts determined from other 850 µm surveys as labeled on the Figure. The long-dashed curve in the lower left corner of the plot indicates the expected 850 µm number counts assuming no evolution of the local luminosity function. Figure reproduced from Coppin et al. (2006).
galaxies after a correction for dust-extinction (Adelberger & Steidel, 2000) is shown as the blue data-points and blue dashed curve. This indicates that the major phase of star-formation activity occurs at even earlier epochs than that determined from optical surveys with no correction for dust-obscuration. However, the SFRs of SMGs could be severely overestimated if a significant fraction of the dust is heated by intense radiation from the accretion of mass onto a central super-massive black-hole, which is observed as an active galactic nucleus (AGN). From a study of the X-ray properties of $S_{850\mu m} > 4$ mJy radio-detected SMGs, Alexander et al. (2003, 2005) determined that while 75% of bright SMGs host AGN, the bolometric luminosity (most of which is emitted at FIR–mm wavelengths) is dominated by star-formation with rates of $\sim 1000\ M_\odot$/yr. This result is consistent with the optical and mid-IR properties of SMGs (Pope et al., 2006; Ashby et al., 2006; Dye et al., 2008; Pope et al., 2008; Clements et al., 2008; Menéndez-Delmestre et al., 2009; Hainline et al., 2009), which in contrast to those of local ULIRGs are generally best-fit by starburst, rather than AGN-like, spectra. The ubiquity of AGN in SMGs strengthens the evidence for an evolutionary connection between these systems and massive elliptical galaxies, since low-redshift AGN are known to be hosted exclusively in massive ellipticals (Dunlop et al., 1993) and optically-selected AGN at high-redshift also have optical/near-IR properties consistent with elliptical galaxies (Aretxaga et al., 1998). In fact, the tight correlation between the mass of the nuclear black-hole and the stellar velocity dispersion of spheroids in the local Universe (Gebhardt et al., 2000a,b) suggests that all galaxies may have experienced an AGN phase in their history which is concurrent with a major epoch of star-formation (Magorrian et al., 1998).

Progress in understanding the nature of SMGs has however been slow, hampered by the difficulty of identifying unambiguous multi-wavelength counterparts to these sources. This arises from the large positional uncertainty of SMGs due to the low spatial resolution (full width at half maximum FWHM $> 10''$) of the telescopes and
the low signal to noise ($S/N$) of the detections combined with the large areal density of sources in deep surveys at shorter wavelengths. Assuming that the FIR to radio correlation observed in the local Universe (Condon, 1992) holds at high-redshift (Ibar et al., 2008; Murphy et al., 2009; Younger et al., 2009), many groups have been able to identify secure radio counterparts to a large number of SMGs (Chapman et al., 2005; Pope et al., 2006; Ivison et al., 2007; Chapin et al., 2009), where the low source density of radio-detected galaxies makes the probability of chance association small. However, this radio-detected sub-sample is potentially biased against SMGs at very high redshift ($z > 3$) due to the strong selection effect with redshift at radio wavelengths (e.g. Carilli & Yun, 1999, see also Figure 1.4); a growing number of SMGs are indeed known to lie at higher redshifts (e.g. Younger et al., 2007, 2009; Schinnerer et al., 2008; Daddi et al., 2009a,b). Consequently, the redshift distribution of SMGs may actually peak at $z > 2.2$. Furthermore, 30% of the radio-detected SMGs in the Chapman et al. (2005) sample were not detected with optical spectroscopy, so this distribution is also biased against the most obscured systems. CO line observations offer the most direct measurement of spectroscopic redshifts for these sources. However, only $\sim 25$ bright SMGs have been observed in CO with the IRAM Plateau de Bure Interferometer (PdBI) (Downes & Solomon, 2003; Genzel et al., 2003; Neri et al., 2003; Sheth et al., 2004; Greve et al., 2005; Kneib et al., 2005; Tacconi et al., 2006, 2008; Schinnerer et al., 2008; Daddi et al., 2009a,b) and with the Combined Array for Research in Millimeter-Wave Astronomy (CARMA) (Frayer et al., 2008). The small instantaneous bandwidth of mm-receivers currently limits CO observations to SMGs with previously known redshifts.

Establishing the connection between SMGs and other high-redshift populations has also been difficult, since current surveys of SMGs cover only a narrow range of flux density and are only sensitive to $L_{\text{FIR}} \gtrsim 3 \times 10^{12} \ L_\odot$ systems, whereas LBGs and LAEs are typically less intense star-forming galaxies with $L_{\text{FIR}} \lesssim 10^{11} \ L_\odot$ (Chapman et al.,
2000; Carilli et al., 2007). Since the SMGs detected to date account for only $\sim 30\%$ of the CIB at 850 $\mu$m, it is clear that a significant population of low-luminosity, dust-obscured star-forming galaxies at high-redshift has yet to be detected. The limited sensitivity of SMGs surveys primarily arises from the low angular resolution of these observations. As the number density of sources approaches the number of independent beams, individual galaxies become blended, or confused, in the map. Since there is a steep rise in the number density of SMGs with decreasing flux density (Figure 1.5), this blending becomes more severe as the map sensitivity increases, and deep surveys are ultimately limited in their sensitivity to individual galaxies. For SCUBA on the JCMT for example, the 850 $\mu$m confusion-limit occurs at $5\sigma_{850\mu m}\approx 2$ mJy. In order to detect submm/mm-sources below this confusion-limit, several observations towards moderate-redshift galaxy clusters at $z < 0.5$ have been carried out to exploit the natural magnification of intrinsically faint background sources by gravitational lensing (e.g. Smail et al., 1998, 2002; Chapman et al., 2002). Using this method a handful ($\sim 5$) of $L_{\text{FIR}} \sim 10^{11} L_{\odot}$ SMGs have been detected (Knudsen et al., 2008); however, there has not been enough overlap between these surveys and those of optical/UV-selected high-redshift galaxies to establish the link between these various populations. Furthermore, these lensing cluster surveys have provided only weak constraints on the number counts of $S_{850\mu m} < 2$ mJy SMGs (Figure 1.5).

The push for higher resolution has driven the design of new submm/mm facilities which will become available in the near future, including the Large Millimeter Telescope (LMT; Schloerb, 2008), and the Atacama Large Millimeter Array (ALMA; Hills & Beasley, 2008; Wootten & Thompson, 2009). The LMT is a single-dish 50-m telescope under construction in Puebla, Mexico, and is a bi-national collaboration between the United States and Mexico lead by the University of Massachusetts, Amherst (UMass) and the Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE). With $\text{FWHM} = 5''$ resolution at 1.1 mm, multi-wavelength counterpart
identification of SMGs detected in surveys with the LMT will be straightforward, and the lower confusion-limit will enable the detection of dusty $L_{\text{FIR}} \sim 10^{11} \, L_\odot$ ($\text{SFR} = 10 - 50 \, M_\odot/\text{yr}$) galaxies at high-redshift: i.e. systems likely to overlap significantly with optical/UV-selected populations of galaxies in the early Universe. Additionally, the redshift search receiver (Erickson et al., 2007) operating at 3 mm on the LMT will have an instantaneous bandwidth of 32 GHz, allowing blind searches for redshifted CO lines from these SMGs without the need for prior redshift information. ALMA will be a 64-element submm/mm interferometer operating at 0.3–9.6 mm and will be capable of 15 milli-arcsec resolution at 1.1 mm. While the small field-of-view precludes its use as a surveying instrument, ALMA will be used to image previously detected SMGs with enough spatial resolution to determine the geometry of the dust emission in these galaxies. This will help to better establish whether the star-formation is taking place within well-defined disks, in multiple systems in the process of merging, or is concentrated to a torus surrounding a nuclear black-hole, and thus whether star-formation or AGN activity is the dominant heating mechanism of the dust. The LMT and ALMA will thus be highly compatible, with the thousands of high-redshift dusty galaxies detected in large-area surveys with the LMT providing a large number of targets for detailed high-resolution imaging with ALMA.

At this stage, however, it is still possible to study galaxy formation through the information provided by wide-area surveys of the bright SMG population, as their number counts are an important ingredient in constraining galaxy evolution models (Guiderdoni et al., 1998; Blain et al., 1999; Devriendt & Guiderdoni, 2000). Semi-analytical models of galaxy formation, which use parametric prescriptions for the physics of baryons in the paradigm of the standard hierarchical scenario in which massive galaxies are built up from the merging of smaller ones, are able to reproduce the luminosity function of LBGs as well as the optical/IR properties of local galaxies. However, the same models severely under-predict the number density of SMGs (e.g.
Cole et al., 2000; Somerville et al., 2001; Menci et al., 2002). This can be remedied by assuming a top-heavy initial mass function (IMF) for star-formation taking place in intense bursts compared to that of more quiescent star-forming galaxies observed locally (Kennicutt, 1983), so that a larger fraction of high-mass stars is formed. This assumption is plausible given the fact that major mergers at high-redshift are more frequent and more intense than those in the local Universe due to higher source density and being more gas-rich. Models that invoke a top-heavy IMF succeed in reproducing both the luminosity function of LBGs and the number density of SMGs (Baugh et al., 2005; Swinbank et al., 2008) as well as the evolution in the mid-IR luminosity function (Lacey et al., 2008). However, the large masses and high SFRs in SMGs appear more consistent with the traditional “monolithic collapse” scheme in which massive individual galaxies form near the bottoms of deep gravitational potential wells, undergo a single intense starburst, and then evolve passively (Eggen et al., 1962). While the monolithic collapse scenario does not fit into the standard scenario for structure formation based on primordial density perturbations, it is possible that complex baryonic processes, which are still poorly understood, act to reverse the order of structure formation for luminous matter from that predicted of cold dark matter. For example, models that include baryonic processes like feedback from supernovae (SNe) and AGN – which can suppress the cooling of gas in small dark matter halos and thus allow massive galaxies to assemble earlier – have likewise been able to describe the observed number counts at mid-IR and submm wavelengths (Granato et al., 2001, 2004; Silva et al., 2005).

The constraints on the 850 µm number counts are unfortunately insufficient to differentiate between various galaxy evolution models due to the limited area and the small flux range probed by these surveys. Since any viable model of galaxy evolution must be able to reproduce the observed properties of galaxies at all wavelengths and all redshifts, the submm/mm number counts at faint flux densities ($S_{850\mu m} \lesssim 2$ mJy)
provide important constraints on such models, as these faint SMGs begin to overlap with optical/UV-selected high-redshift galaxy populations. The only constraints on the 850 \( \mu m \) number counts at \( S_{850\mu m} \lesssim 2 \) mJy are provided by surveys towards massive lensing clusters, as this is the only method to detect individual galaxies below the 850 \( \mu m \) confusion-limit. As evident from the large errors bars for this data (Figure 1.5), measurements of the faint-end of the number counts are limited by small number statistics. Furthermore, number counts estimated from lensing cluster surveys involve several corrections (e.g. de-magnification of source flux densities and source-plane area) that require detailed models of the mass distribution of the lensing cluster as well as the redshifts of the background SMGs, both of which are generally not well known.

At the other extreme, measuring the bright-end of the SMG number counts is also critical for discriminating between models of galaxy evolution, as they provide important limits on the number and luminosities of the most extreme systems that can form. As the number density of sources falls off quickly with increasing flux density (Figure 1.5), it is necessary to survey large areas in order to detect a statistically significant number of bright SMGs. The largest 850 \( \mu m \) survey is the 0.25 deg\(^2\) SCUBA Half Degree Extragalactic Survey (SHADES; Coppin et al., 2006, filled circles in Figure 1.5), which provided the first definitive measurement of the steepening of the number counts above \( S_{850\mu m} > 8 \) mJy. SHADES is also the only 850 \( \mu m \) survey with enough statistical power to measure the differential number counts – the source density per flux – which provides better constraints on galaxy evolution models than the (highly correlated) cumulative number counts. However, by comparing the SHADES results to number counts from the other surveys shown in Figure 1.5, there is a large amount of field-to-field variation in the SMG population. This could be entirely due to statistical variance given the limited survey areas; however, this may also be a sign of true cosmic variance arising from large-scale structure. Unfortunately, the limited
amount of area covered at 850 µm precludes a study of the degree of cosmic variance in the observed number counts, and it is yet unclear whether the SHADES results represent the average number density for the SMG population. The same is true for the 1.1 mm number counts derived from Bolocam and MAMBO surveys: while a total of 0.3 deg$^2$ has been imaged, the data have been reduced and analyzed in very different ways, making it difficult to collectively study these fields for signs of cosmic variance in the number counts. Furthermore, none of the papers reporting on these observations have published the differential number counts from these fields (Greve et al., 2004, 2008; Laurent et al., 2005; Bertoldi et al., 2007).

Large-area submm/mm surveys of the bright SMG population may also reveal whether these systems are linked to the formation phase of massive elliptical galaxies. While this evolutionary connection is feasible given their intense SFRs, which if persisting for $\sim 1$ Gyr could build up the stellar population observed in local elliptical galaxies, many groups have suggested that SMGs are rather associated with short-lived ($\sim 100$ Myr), intense bursts of star-formation occurring in more modest galaxies like LBGs (e.g. Adelberger & Steidel, 2000; Chapman et al., 2009). If SMGs are the progenitors of massive elliptical galaxies, they should trace the most massive peaks in the underlying dark matter distribution and would be more strongly clustered than a population of less massive galaxies as a result of gravitational collapse from Gaussian primordial density fluctuations, since the rare high-mass peaks are strongly biased with respect to the mass (Kaiser, 1984; Benson et al., 2001). There is tentative evidence based on small-area, disjoint surveys and incomplete redshift information (Blain et al., 2004; Scott et al., 2006) that SMGs cluster on scales comparable to those measured for red, massive $z \gtrsim 1$ galaxies (Daddi et al., 2000). Additionally, over-densities in the number density of SMGs have been reported in observations towards regions with known over-densities of high-redshift sources detected at other wavelengths (e.g. Best, 2002; Ivison et al., 2000; Stevens et al., 2003), suggesting that
SMGs may indeed trace the highest density structures like proto-clusters in the early Universe. However, in order to definitively measure the clustering properties of bright SMGs on co-moving scales of interest ($\geq 10$ Mpc; see van Kampen et al., 2005, and references within), large contiguous regions nearing $1 \, \text{deg}^2$ must be mapped.

Since the pioneering work of SCUBA, continuing advances in instrumentation have improved the sensitivity and large-area mapping capabilities of mm-wavelength bolometric array cameras. A new mm-wavelength camera, AzTEC (Wilson et al., 2008), has been designed and built for operation as a facility instrument on the LMT. Awaiting completion of the LMT, we commissioned AzTEC at 1.1 mm during an engineering run at the JCMT in June 2005 and completed a successful observing run at the JCMT from November 2005 to February 2006. With five weeks (350 hours) of observing time devoted to mm-galaxy surveys, we imaged $\sim 1$ deg$^2$ with uniform sensitivity ($1\sigma = 1.0 - 1.4$ mJy), doubling the area mapped previously by SCUBA, MAMBO, and Bolocam combined. In May 2007 we installed the instrument on the 10-m Atacama Submillimeter Telescope Experiment (ASTE) for two seasons of observations from June–October 2007 (Ezawa et al., 2008) and July–December 2008. A total of 1500 hours went into mm-galaxy surveys towards both blank-fields and regions with known galaxy over-densities, with a total area of 3 deg$^2$ mapped to sensitivities of $1\sigma = 0.3 - 1.5$ mJy. These projects have resulted in the detection of $\sim 1000$ bright SMGs located within some of the most widely studied fields at all wavelengths, including the COSMOS field, the Great Observatories Origins Deep Survey-North and -South (GOODS-N and GOODS-S), the Lockman Hole-East (LH-E), the Subaru/XMM-Newton Deep Field (SXDF), and the South Ecliptic Pole (SEP). This wealth of deep, multi-wavelength complementary data, including radio interferometric imaging with the Very Large Array (VLA), mid-IR photometry from Spitzer IRAC/MIPS, optical imaging and spectroscopy from the Hubble Space Telescope (HST) and several ground-based facilities, and X-ray imaging from Chandra,
allows the immediate analysis of the properties of these sources. These surveys have also provided a homogeneous sample of bright mm-galaxies that are obvious targets for the first observations with the redshift search receiver on the LMT and for high-resolution imaging with ALMA, once these new facilities become available. The 1.74 deg$^2$ of blank-fields surveyed provide the tightest constraints on the SMG number counts, which will help to discriminate between various galaxy evolution scenarios. Since all of the fields imaged with AzTEC have been analyzed using the same well-tested methods, this data-set provides the first opportunity to measure the degree of cosmic variance in the number counts of this population, and the large contiguous regions mapped will allow measurements of the clustering properties of these sources.

The material presented here includes much of the earliest work to characterize the performance of the AzTEC camera and results from the SMG surveys taken with AzTEC on the JCMT and ASTE. In Chapter 2 we describe general properties of the instrument, including the detector point spread functions, sensitivities, the mapping speed of the instrument, and flux calibration. In Chapter 3 we present the AzTEC survey of the COSMOS field, including the map, source catalog, number counts, and successful follow-up of the bright SMGs in this field with submm interferometry. We have developed custom data reduction methods for AzTEC which are optimized for the detection of point sources, and we describe these in Chapter 3 as well. The AzTEC survey of the GOODS-S field is presented in Chapter 4, including the map, source catalog, number counts, and the identification of multi-wavelength counterparts to the mm-sources. In Chapter 5, we combine the results from all blank-field surveys taken with AzTEC on the JCMT and ASTE to determine the most accurate number counts to date at 1.1 mm, covering a total area of 1.74 deg$^2$. We conclude with a summary of the advancements in the field of submm/mm astronomy that have been made with these AzTEC surveys in Chapter 6.
CHAPTER 2
PERFORMANCE OF THE AZTEC
MILLIMETER-WAVELENGTH CAMERA

2.1 Introduction

AzTEC (Wilson et al., 2008) is a millimeter- (mm-) wavelength continuum camera developed at the University of Massachusetts, Amherst (UMass) in collaboration with researchers at Caltech, Cardiff University, the Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE), Sejong University, and Smith College for operation on the Large Millimeter Telescope (LMT). Its 144 silicon nitride micro-mesh bolometers operate with a single bandpass centered at either 1.1, 1.4, or 2.1 mm, with one bandpass available per observing run. In its 1.1 mm-wavelength configuration, AzTEC is sensitive to the Rayleigh-Jeans tail of the thermal continuum emission from cold dust grains, and is well-suited for large, deep extragalactic surveys of dusty, optically-obscured starburst galaxies detected by their submm/mm emission. AzTEC’s high mapping speed and high sensitivity also allow studies of cold dust in the Milky Way and in nearby galaxies. Configured for 1.4 mm and 2.1 mm observations, AzTEC will enable high-resolution images of the Sunyaev-Zel’dovich effect in clusters of galaxies (Sunyaev & Zeldovich, 1972). AzTEC on the LMT will have a per-pixel resolution of 10″ at 2.1 mm (5″ at 1.1 mm) and will therefore be an unprecedented instrument for the study of the energetics of the free electron gas in clusters.

Details of the design of the AzTEC camera are given in Wilson et al. (2008). In this Chapter we report on the characteristics and performance of AzTEC while operating at 1.1 mm on the James Clerk Maxwell Telescope (JCMT) from November 2005 to February 2006 (referred to hereafter as the JCMT05B observing run).
and the Atacama Submillimeter Telescope Experiment (ASTE) from June–October 2007 (ASTE07 observing run) and July–December 2008 (ASTE08 observing run). In Section 2.2 we describe the beam-mapping measurements used to characterize the bolometers’ point spread functions and to determine their relative positions on the sky. In Section 2.3 we describe how these measurements are used for absolute flux calibration of the AzTEC data. We discuss the performance of AzTEC, including detector sensitivities and array mapping speed, in Section 2.4. We conclude with a discussion of AzTEC’s expected performance on the LMT in Section 2.5.

2.2 Point Spread Functions and Positional Offsets

2.2.1 Beam-Maps

Combining the signals from an array of detectors requires accurate measurements of their relative sky positions with respect to the telescope boresight, as well as the point spread functions (PSFs) and flux conversion factors of each detector for absolute flux calibration. We determine these properties by “beam-mapping” a bright point source with known flux density at least once per night. A beam-map consists of a high-resolution raster-scan observation, where the telescope scans across the sky at constant velocity along one direction (azimuth or elevation), takes a small step in the orthogonal direction, and then sweeps back in the opposite direction. This pattern is repeated until the entire field has been mapped. For our beam-maps, we image a $6.7 \times 6.7$ arcmin$^2$ field for the JCMT (10 × 10 arcmin$^2$ for ASTE) so that every bolometer fully samples the point source. We use a small step size of 4″ for JCMT beam-maps (6″ for ASTE beam-maps) so that we can measure the relative bolometer sky positions to an accuracy of $\approx 5\%$ of the PSF full width at half maximum (FWHM). We use high scan speeds (60 – 100″/s) in order to move the signal bandwidth above the knee frequency of residual atmospheric contamination (Section 2.4.1).
Because of the low-frequency stability of the detectors, we do not need to chop the secondary mirror to subtract the common-mode signal that is dominated by atmospheric water vapor emission. Instead, we use a simple average-subtraction cleaning to remove the low-frequency signal correlated across the array. Raw AzTEC data consists of bolometer signals and telescope pointing signals stored as a function of time (hereafter “time-stream” signals). Given the small array field-of-view we only consider temporal correlations among detectors as the spatial correlations will be implicitly accounted for as well. The time-stream signals are first despiked as described in Section 3.3.1 to remove any $> 10\sigma$ deviations between sequential bolometer samples which correspond to cosmic ray strikes or instrumental glitches. We then group the data into scans for cleaning. We discard samples recorded between scans when the telescope turns around since the accuracy of the pointing signals during these high telescope accelerations is unknown. We subtract a baseline for each scan, or “dc-level”, for each bolometer separately, masking the bright point source by excluding signal $> 3\sigma$. The sample-average over all bolometers for each time-stream datum is then subtracted. We then bin and average these cleaned samples into “delta-source” azimuth–elevation space, i.e. tangent to the known position of the point source. A separate beam-map is made for each bolometer.

An example beam-map for a single bolometer from an observation taken during the JCMT05B run is shown in the left panel of Figure 2.1. As with all JCMT05B beam-maps we scan the telescope in the elevation direction to avoid vibration-induced noise at 2.5 Hz observed when scanning in the azimuthal direction. While this results in a continuously changing optical loading on the detectors during the scan, we find that this does not adversely affect our atmosphere removal as the sample-average subtraction removes this effect. For ASTE beam-maps, no such vibration-induced noise is observed, so we scan in both directions throughout both observing runs. The “striping” along the scan direction in Figure 2.1 highlights residual low-frequency
atmospheric emission that is not removed with this simple average-subtraction cleaning. While this does not greatly affect our measurements from beam-maps on bright point sources where the signal to noise is very high ($S/N > 20$), we use a more sophisticated technique for common-mode subtraction based on a principal component analysis (PCA) when the astronomical signal is dominated by the spatially and temporally variable atmospheric emission (see Section 3.3.2).

2.2.2 Measuring Relative Offsets and Point Spread Functions

On the JCMT and ASTE, the AzTEC instrument is mounted such that the array orientation is fixed in azimuth and elevation, and so the relative offset on the sky between any two detectors is constant. We determine the relative offset of each bolometer and its PSF by fitting its beam-map to a 2-dimensional Gaussian with six
free parameters: \((Q_0, Q_1, \Delta Az, \Delta El, \sigma_{Az}, \sigma_{El})\), where \(Q_0\) is a constant baseline offset (in pW, nearly zero after atmospheric subtraction), \(Q_1\) is the peak signal (in pW), \(\Delta Az\) and \(\Delta El\) are the positional offsets in azimuth and elevation, respectively, of the bolometer with respect to the telescope boresight, and \(\sigma_{Az}\) and \(\sigma_{El}\) are the widths (= \(\frac{\text{FWHM}}{2\sqrt{2\ln(2)}}\)) of the beam in azimuth and elevation. For the example beam-map in Figure 2.1, the red horizontal and vertical lines indicate the measured bolometer offsets from the telescope boresight. The beams are nicely Gaussian down to the first side-lobe response at \(-20\) dB.

The AzTEC array is organized into six pie shaped regions (hextants) that contain the 144 optically active bolometers and their wiring. For the array configuration at the JCMT and ASTE, there is no bolometer located at the array center that follows the tracking of the telescope boresight. Since we do observe small deviations from the telescope pointing model \((\approx 2 - 3''\))\), we correct for these with frequent pointing observations as described in Section 3.2.1. As these do not affect the relative sky positions between detectors, we record the bolometer offsets with respect to that of a reference bolometer located near the array center. The array “footprint” on the sky centered at the reference bolometer for the JCMT05B and ASTE07 observing runs is shown in Figure 2.2, with the six hextants labeled (the ASTE07 and ASTE08 layouts are nearly identical). All detectors that were not fully operational with high sensitivity are excluded, leaving 107, 107, and 117 operational bolometers for the JCMT05B, ASTE07, and ASTE08 seasons, respectively. The majority of failures in the signal chains have been traced to broken JFET amplifiers which will be repaired by 2009 for AzTEC operations on the LMT.

The bolometer positions and beam sizes shown in Figure 2.2 are determined by averaging the measurements from all beam-maps taken during the respective observing runs. The size of the ellipse is equal to the beam FWHM, which is measured in the azimuth and elevation directions and is on average \(17'' \pm 1''\) in azimuth and
Figure 2.2. AzTEC’s “footprint” on the sky at the 15-m JCMT (left) and the 10-m ASTE (right), with the six hextants labeled. The alternating colors indicate which bolometers are located in each hextant. The size of the ellipse corresponds to the bolometer’s FWHM, measured in the azimuth and elevation directions. The plots are shown with the same physical scale to highlight the differences in the beam sizes and array field-of-view given the telescope diameters.
Table 2.1. AzTEC 1.1 mm optical parameters and performance metrics for the JCMT and ASTE observations. The effective bandwidth is calculated assuming a flat-spectrum source and is the same for all observing runs. The other quantities are measured as discussed in the text.

<table>
<thead>
<tr>
<th></th>
<th>JCMT05B</th>
<th>ASTE07</th>
<th>ASTE08</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band center frequency</td>
<td>270.5 GHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Effective bandwidth</td>
<td>49.0 GHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam FWHM (azimuth)</td>
<td>17″ ± 1″</td>
<td>30″ ± 1″</td>
<td>31″ ± 1″</td>
</tr>
<tr>
<td>Beam FWHM (elevation)</td>
<td>18″ ± 1″</td>
<td>31″ ± 2″</td>
<td>29″ ± 1″</td>
</tr>
<tr>
<td>Array field-of-view</td>
<td>5.0′</td>
<td>8.0′</td>
<td>8.1′</td>
</tr>
</tbody>
</table>

18″ ± 1″ in elevation for AzTEC on the JCMT. An off-axis ellipsoidal mirror in the optics chain for the JCMT (Wilson et al., 2008) leads to a slight elongation of the beam in the elevation direction. The AzTEC/JCMT array field-of-view is roughly circular with a diameter of 5.0′. The relative bolometer offsets, which are needed in order to combine the bolometer signals in map-space, vary only slightly (1σ < 1.5″) during the entire two months of observing on the JCMT, so we use the relative positional offsets averaged over all 35 beam-maps on Uranus taken during JCMT05B for map-making purposes.

At the ASTE, the beam FWHM is ≈ 30″ in both azimuth and elevation and the array field-of-view is 8.0′. A summary of the optical parameters and performance of AzTEC at 1.1 mm for the JCMT and ASTE are given in Table 2.1. The differences in the beams between the two seasons on ASTE is due to slight changes in the sub-reflector position, which leaves the beams slightly elongated in elevation (azimuth) for the ASTE07 (ASTE08) operations. As with the JCMT observations the relative bolometer offsets vary by 1σ < 1.5″ over the course of a single observing season on ASTE.
2.3 Flux Calibration

2.3.1 Flux Conversion Factor

The output of bolometer $i$ at sky position $\Omega_0$, $b_{i,0}$ (in units of V), is given by

$$b_{i,0} = S_i(Q)A_{\text{eff}}\eta \int_0^\infty d\nu f(\nu) \int_{\text{sky}} d\Omega P_i(\Omega_0 - \Omega) e^{-\tau_{\text{eff}}} I_\nu(\Omega),$$  \hspace{1cm} (2.1)

where $S_i(Q)$ is the responsivity (in V/W), $Q$ is the optical loading (in W) dominated by the telescope and atmosphere, $A_{\text{eff}}$ is the effective telescope aperture, $\eta$ is the optical efficiency, $f(\nu)$ is the peak-normalized AzTEC bandpass, $P_i(\Omega_0 - \Omega)$ is the peak-normalized AzTEC beam pattern for bolometer $i$ at sky position $\Omega_0$, $\tau_{\text{eff}}$ is the opacity, and $I_\nu(\Omega)$ is the source intensity on the sky (in Jy beam$^{-1}$). As discussed below, we model $S_i$ and $\tau_{\text{eff}}$, both of which depend on observational conditions (e.g. weather) and change significantly on the time scale of hours, as functions of the dc-level of the bolometer signal.

The flux conversion factor (FCF) for bolometer $i$, FCF$_i$ (in units of Jy beam$^{-1}$ W$^{-1}$), is an expression involving all factors that are, in principle, constant (i.e. source and weather independent) over the entire observing run, and is defined as

$$\text{FCF}_i = \frac{1}{A_{\text{eff}}\eta \int_0^\infty d\nu f(\nu) \int_{\text{sky}} d\Omega P_i(\Omega_0 - \Omega)}. \hspace{1cm} (2.2)$$

For a point source located at $\Omega_0 = (\theta_0, \phi_0)$ with average flux density $\bar{I}$ over the optical bandpass, the bolometer output is

$$b_i(\theta_0, \phi_0) = \frac{S_i(Q)e^{-\tau_{\text{eff}} \bar{I}}}{\text{FCF}_i}. \hspace{1cm} (2.3)$$

2.3.2 Responsivity and Extinction Corrections

Once AzTEC is installed on a telescope the only free parameter for optimizing sensitivity is the amount of electrical (bias) power dissipated at the bolometer and
hence the bolometer operating temperature. For a given set of detector properties and a given optical loading the balance between phonon noise (which rises with temperature) and Johnson noise (which falls steeply with rising temperature) results in an optimum value of the bias voltage (Mather, 1984). Since there is a small spread in detector properties across the array and a slowly varying, but unpredictable, optical loading due to the atmosphere, we fixed the thermistor bias amplitude for all detectors at 62.5 mV for both the JCMT05B and ASTE observing runs (Wilson et al., 2008). For an atmospheric optical depth at 225 GHz $\tau_{225} = 0.1$, this conservatively high bias results in a sensitivity 10% worse than expected for a bolometer that meets the design parameters.

We determine the total optical power $Q$ absorbed by each detector as well as the responsivity $S_i$ (the conversion from Volts read out of the detector to Watts absorbed) of each detector from load-curve measurements, where we move the detector bias voltage through its full range of commandable values while viewing a blank patch of sky. Load-curves are performed 1 – 2 times per night over a range of elevation; by measuring the responsivity under a wide range of atmospheric opacities we construct a correction to the non-linearity of the detector response due to the overall variation in the atmospheric optical loading. For the range of total power loading on the detectors observed during the JCMT05B and ASTE observing runs, the responsivity is linearly proportional to the demodulated dc-level of each bolometer’s time-stream signal. The responsivity of a typical bolometer versus the dc-level measured from all of the load-curve observations taken during the JCMT05B (black data-points) and ASTE07 (red data-points) observing runs is shown in the left panel of Figure 2.3. The solid curves show the linear fits to the measurements for the two observing runs, which are essentially the same. We derive the best-fit offset and slope for each bolometer separately since the spread in these parameters is large compared to the formal errors on the fits.
Figure 2.3. The dependence of the detector responsivity and atmospheric opacity on the bolometer dc-level. Left: Responsivity versus bolometer dc-level for a typical detector as determined from all of the load-curves taken during the JCMT05B (black data-points) and ASTE07 (red data-points) observing runs. The best-fit lines for the two separate observing runs are over-plotted. Right: Atmospheric opacity, $\tau_{\text{eff}}$, versus bolometer dc-level for the same detector. The horizontal dashed line marks $\tau_{\text{eff}} = 0.25$; we exclude all data taken above this limit in determining the best-fit line and we do not consider scientific observations taken when $\tau_{\text{eff}} > 0.25$. 
The atmospheric extinction $e^{-\tau_{\text{eff}}}$ is corrected in a similar way. For the JCMT data we use the atmospheric opacity at 225 GHz as determined from the Caltech Submillimeter Observatory (CSO) tau monitor, which records $\tau_{225}$ (zenith) every 10 minutes, to calibrate the linear correlation between the atmospheric opacity $\tau_{\text{eff}}$ ($= \tau_{225} \cdot A$, where $A$ is the airmass) and the bolometer dc-levels (right panel of Figure 2.3, black data-points and solid line). We do the same for the ASTE07 and ASTE08 data (red data-points and line), where the atmospheric zenith opacity at 220 GHz ($\tau_{220}$) is recorded at a rate of 10 Hz by the ASTE tau monitor (here $\tau_{\text{eff}} = \tau_{220} \cdot A$). These data span the entire range of $\tau_{\text{eff}}$ for which scientific observations were carried out at both the JCMT and ASTE. The difference between the JCMT05B and ASTE07 data is due in part to the different frequencies used by the CSO and ASTE tau monitors, but also arises from the difference in optical loading from the telescopes. From Figure 2.3 we can see that the relationship between $\tau_{\text{eff}}$ and the bolometer dc-level is slightly non-linear. A fit to the data using a 2-dimensional polynomial only slightly improves the goodness-of-fit and results in a difference of $\leq 2.5\%$ in the estimated extinction (i.e. $e^{-\tau_{\text{eff}}}$) for $\tau_{\text{eff}} < 0.25$, with the error increasing as a function of $\tau_{\text{eff}}$. Given this small improvement, we use the linear approximation and restrict all analysis to scientific observations taken with $\tau_{\text{eff}} < 0.25$.

2.3.3 Measured Flux Conversion Factor from Beam-Map Observations

To determine the FCF$_i$, we beam-map a primary (planet) or secondary flux calibrator at least once per night. We correct the time-stream bolometer signals for extinction and factor out the responsivity so that the resulting beam-map is in units of Watts. We then fit each beam-map to a 2-dimensional Gaussian as described in Section 2.2.2. Although we mask the brightest signal in the bolometer time-streams by the $> 3\sigma$ cut used in the atmosphere removal, the remaining low-level signal from the point source has a non-negligible effect on the average-subtraction, resulting in
attenuation of the astronomical signal. For this reason we use an iterative cleaning technique to minimize systematic errors in the fitted parameters, which proceeds as follows: 1) the best-fit Gaussian profile to the beam-map for a given bolometer is subtracted from the raw (pre-cleaned) time-stream data; 2) the residuals are cleaned using the same average-subtraction technique and are then cast into map-space; 3) the best-fit Gaussian from Step 1 is added to the residual map; and 4) the new map from Step 3 is refit to update the parameter estimates. This process recovers a significant fraction of the signal lost in the first pass of cleaning. Steps 1–4 are repeated until the fitted parameters change by < 5% between successive iterations; this is typically accomplished in ≤ 5 iterations. The best-fit amplitude from the final beam-map combined with the known flux density of the calibrator gives the FCF.

Only Uranus and Neptune can be used as primary flux calibrators for AzTEC on the JCMT and ASTE, since the other planets are either too bright at 1.1 mm (i.e. in the non-linear response regime of the detectors) or are considerably extended (i.e. not point sources); however, both planets have a non-negligible angular extent (diameter = 2–4") compared to the AzTEC beam. In order to account for this in the calibration, we assume that the planet is a disk with angular radius ΘP and brightness temperature Tb(ν) so that \[ I_ν(Ω) = \frac{2kT_b(ν)ν^2}{c^2}\Phi(Ω), \] where \( \Phi(Ω) = 1 \) for \( θ ≤ Θ_P \) and 0 otherwise. The frequency-dependent \( T_b(ν) \) is taken from Griffin & Orton (1993) and is 92.6 ± 1.7 K and 87.9 ± 1.8 K for Uranus and Neptune, respectively, at the AzTEC center frequency. The average flux density of the planet in the AzTEC beam for bolometer \( i \) is then given by

\[
\bar{I}_i = \frac{\int_0^∞ dν f(ν)\frac{2kT_b(ν)ν^2}{c^2}\int_{sky} dΩ P_i(Ω_0 − Ω)\Phi(Ω)}{\int_0^∞ dν f(ν)\int_{sky} dΩ P_i(Ω_0 − Ω)}. \tag{2.4}
\]

Uranus and Neptune are relatively small compared to the AzTEC detector PSFs on the JCMT and ASTE \( (2Θ_P ≪ θ_{bi}, \) where \( θ_{bi} \) is the true beam FWHM for bolometer \( i \) and so will appear approximately Gaussian with a measured FWHM \( θ_{mi}, \) where
\[ \theta_{bi}^2 = \theta_{mi}^2 - \frac{\ln 2}{2} (2\Theta_P)^2 \]  

(Baars, 1973). We measure \( \theta_{mi} \) from the beam-maps and use Equation 2.5 to determine \( \theta_{bi} \) and subsequently \( P_i(\Omega) \). We then calculate the flux density of the planet \( \bar{I}_i \) using Equation 2.4, which is roughly the same for all AzTEC bolometers given the small range in beam sizes. \( \bar{I}_i \) varies between 41 – 52 Jy for Uranus and 18 – 20 Jy for Neptune at 1.1 mm given the change in angular size during the observing runs. We use these values of \( \bar{I}_i \) in Equation 2.3 along with the measured peak flux from the beam-maps to determine the FCF \( i \) for each detector.

2.3.3.1 JCMT Calibration

Uranus was the only primary calibrator available for the JCMT05B observing run. From a total of 35 beam-map observations, we find a statistically significant increase in the FCF \( i \) for measurements taken within one hour after sunset, while measurements taken after this time have constant FCF \( i \). This effect is demonstrated for an example bolometer in Figure 2.4, which shows the measured FCF \( i \) as a function of the number of hours after sunset that the beam-map observation took place. This is consistent with rough estimates of the telescope's thermal time constant. For this reason, we determine the average FCF for each bolometer, \( <FCF_i> \), by averaging over all FCF \( i \) measured from Uranus beam-maps taken \( \geq 1 \) hour after sunset, and we use these values to calibrate all science observations taken after the telescope has settled. For this subset of Uranus observations (total of 14) the 1\( \sigma \) scatter on \( <FCF_i> \) is on average 7\%. A linear correction factor derived from the 21 Uranus beam-maps taken within one hour after sunset is applied to science data taken during this period. We model this correction factor \( f \equiv \frac{FCF_i}{<FCF_i>} \) as a linear function of the time after sunset, such that

\[ f = 1 \quad \text{if} \; \text{HAS} \geq 1 \]
Figure 2.4. The measured flux conversion factor (FCF) for an example bolometer for all beam-maps on Uranus taken at the JCMT, shown as a function of the number of hours after sunset (HAS) that the observation took place. The FCF_i decrease continuously until HAS = 1 hr, and then is stable for the remainder of the night. The horizontal line represents the mean FCF_i averaged over all Uranus beam-maps taken when HAS ≥ 1 hr. The line shown for HAS < 1 hr shows the best-fit linear model for the change in the FCF_i with HAS and demonstrates the correction factor f from Equation 2.6 needed for calibrating data taken within one hour before sunset.

\[
= 1 + m \cdot (\text{HAS} - 1) \quad \text{if } \text{HAS} < 1
\]

(2.6)

where HAS is the time after sunset measured in hours, \( m \) is the same factor for all bolometers, and continuity at HAS = 1 hr is required. We fit the measured FCF_i / \(<\text{FCF}_i>\) for all bolometers and all beam-maps with HAS < 1 hr simultaneously to Equation 2.6 and find \( m = -0.115 \pm 0.002 \text{ hr}^{-1} \). This model is shown in Figure 2.4 as the solid curve.
For a given science observation at the JCMT with responsivity $S_i$ and extinction $e^{-\tau_{\text{eff}}}$ measured from the bolometer dc-levels, the calibrated time-stream bolometer signals $\bar{I}_i(t)$ are given by

$$\bar{I}_i(t) = b_i(t) \cdot \frac{<\text{FCF}_i> \cdot f}{S_i \cdot e^{-\tau_{\text{eff}}}}$$

(2.7)

where $f$ is determined from the HAS that the observation took place and Equation 2.6.

The error on the calibrated bolometer signals is therefore equal to the quadrature sum of the errors on all four factors in Equation 2.7 and is typically $5 - 13\%$ for the JCMT05B data. The errors on $S_i$ and $\tau_{\text{eff}}$ (propagated from the empirical fits to the bolometer dc-levels) and the error on $<\text{FCF}_i>$ (standard deviation over measurements from all HAS > 1 hr beam-maps) roughly contribute equally to the total measurement error, whereas the contribution from the uncertainty on $f$ (when applicable) is negligible. This value does not include the 5% absolute uncertainty in the flux density of Uranus (Griffin & Orton, 1993); adding this in quadrature with the measurement errors gives a total calibration error of $7 - 14\%$.

We imaged a handful of secondary flux calibrators at the JCMT, including the bright quasar 3c279, and two proto-planetary nebulae that were frequently used for the calibration of SCUBA data: CRL618 and IRC+10216. We interpolate between flux density measurements of 3c279 at 230 and 345 GHz taken with the Submillimeter Array in mid-November 2005 to determine a flux density of 6.2 Jy at the AzTEC center frequency of 270 GHz. Using this value in Equation 2.3 we get values for the FCF$_i$ that are consistent with those measured from the beam-maps on Uranus. Both CRL618 and IRC+10216 are known to be extended and variable with long-periodicity (Sandell, 1994); with no recent measurements of either source at 270 GHz to quantify this variability we choose not to include these observations for data calibration.
2.3.3.2 ASTE Calibration

Both Uranus and Neptune were available for the ASTE07 and ASTE08 observing seasons, and we additionally mapped the quasars 3c273 and 3c279 as secondary flux calibrators. We obtained in total 111 (261) beam-map observations in 2007 (2008). Compared to the JCMT results, the measured FCF$_i$ from 2007 have a high amount of scatter with $1\sigma = 17\%$; they do not however have a strong dependence on the proximity to sunrise/sunset times of the beam-map observation. Rather, the FCF$_i$ as well as the beam sizes in the elevation direction are anti-correlated with the environment temperature as monitored at the ASTE site (see Figure 2.5), albeit with a large amount of scatter. This trend implies a decrease in the optical power from the observed point source as the FWHM in elevation increases, and is consistent with a changing focal point of the telescope as the outside temperature varies. However, we were not able to adjust the sub-reflector position during normal operations to improve the focus in real-time. We have therefore implemented a preliminary calibration for ASTE data in which we use the FCF$_i$ and positional offsets measured from the same-night beam-map to calibrate the data and co-add the bolometer signals. We estimate the calibration error (including the uncertainty on the flux densities of the primary calibrators) to be 16\% (Section 4.2.3). We plan to improve the calibration in the future by including a temperature-dependence. We achieved better optical alignment for the 2008 season on ASTE and measure a $1\sigma$ scatter of 10\% for the FCF$_i$. Though there does appear to be a correlation between the FCF$_i$ and the environment temperature at $> 0 \degree C$, the FWHM of the beams in the elevation direction do not show a similar trend.
Figure 2.5. The dependence of the flux conversion factor (FCF) and beam full width at half maximum (FWHM) on environment temperature for AzTEC on ASTE. Left: The measured FCF for an example bolometer for all beam-maps taken during the ASTE07 (black) and ASTE08 (red) observing runs as a function of the environment temperature. The horizontal lines represents the mean averaged over all beam-maps. Right: The measured FWHM in the elevation direction for the same bolometer, where the horizontal lines show the average over all beam-maps.
2.4 Performance

2.4.1 Noise and Sensitivity

We use blank-field observations towards regions with no bright mm-sources taken in raster-scan mode to estimate detector noise and sensitivity. Figure 2.6 shows the noise equivalent flux density per beam (NEFD) for a typical detector in three weather conditions at the JCMT: $\tau_{225} = 0.11$, $0.16$, and $0.20$. The thicker curves show the raw NEFDs while the thinner curves of the same color show the improvement due to an atmosphere removal technique based on a principal component analysis (PCA; Laurent et al., 2005, Section 3.3.2). We use this PCA cleaning in all of the analyzes for characterizing the instrument performance described in this Section. The low-frequency features, dominated by atmospheric fluctuations, are not completely projected out by the PCA cleaning. The flatter NEFD at higher frequencies that does not benefit from cleaning can be attributed to the irreducible noise floor due to the photon background limit (BLIP) and detector noise.

The three dashed lines indicate the thermodynamic noise limits for an ideal AzTEC detector given the bias voltage, expected atmospheric optical loading for the three opacities, and optical loading from the telescope (assuming a 15% effective emissivity; Wilson et al., 2008). In each case the actual high-frequency noise level is consistent with the detector and loading model to within $10 - 20\%$, well within our uncertainty of the total optical loading on the detectors. The nearly constant ratio between the achieved and expected noise levels over varying weather conditions indicates that the operationally convenient choice of using a constant bias voltage for the entire observing run had little if any negative impact on sensitivity.

The major benefit to raster-scanning is the ability to map a large area of sky in a single observation with very uniform coverage, as the distribution of inoperable detectors on the array only affects the ultimate sensitivity, not the uniformity of the coverage, in the map. The increase in noise at low-frequency highlights the...
Figure 2.6. The noise equivalent flux density (NEFD) for a typical bolometer. The three colors correspond to $\tau_{225} = 0.11$ (red), 0.16 (blue), and 0.20 (green). The thicker curves represent raw data while the thinner curves show data that have been cleaned using a principal component analysis. The lower-opacity data benefits more from the common-mode subtraction as well as by the reduced optical loading. The dashed lines represent the corresponding NEFDs for a bolometer with targeted detector parameter values at our bias level plus the optical loading from the telescope (Wilson et al., 2008). The dash-dotted and dotted curves indicate the approximate optical bandwidth of a point source at the JCMT and ASTE, respectively, in arbitrary units for a scan velocity of 180″/s.
importance of scanning at high speed in order to move the signal bandwidth above
the knee frequency of residual atmospheric contamination. For example, the dash-
dotted curve of Figure 2.6 indicates the approximate optical bandpass of a detector at
a scan velocity of $180''/s$, which is also the detector point source response at that scan
speed for the JCMT. The dotted curve shows the point source response for ASTE
at the same scan speed. Scan speeds are ultimately limited by the detector time
constant and the stability of the telescope; however, a practical limitation is imposed
by the cost in overall observing efficiency due to the fixed length turn-around time
(5 s) of the telescope. We thus chose scan speeds for raster-scan observations of
$30''/s - 270''/s$ to balance the opposing effects of higher sensitivity and larger turn-
around time fraction at higher scan speeds. We do not see vibration-induced noise
increase within this range of velocities (with the exception of scans along the azimuth
direction for JCMT data as mentioned in Section 2.2.1). We did measure excess noise
near $\sim 2.5$ Hz on bad weather nights at the JCMT (see for example the blue curve
in Figure 2.6), possibly due to wind-induced small motions of optical loads such as
the JCMT’s Gore-tex cover.

The abrupt noise cutoff near 32 Hz is due to a digital filter that conditions the
demodulated bolometer signals for 64-Hz decimation. The attenuation with frequency
between 20 and 30 Hz is due to the bolometer time constant. The line at $\sim 25$ Hz is
likely a side band caused by the third harmonic of AC power (or “60 Hz”) mixed with
the 200 Hz demodulation waveform (Wilson et al., 2008). When analyzing raster-scan
observations we implement a second digital low-pass filter in the software to avoid
aliasing this power back into the signal bandwidth.

The “flat” NEFD near 10 Hz represents a limiting white noise level regardless of
how effectively the low-frequency atmospheric features can be removed using a partic-
ular cleaning method. Therefore, in the left panel of Figure 2.7 we have histogrammed
these ultimate sensitivities on the JCMT for the working detectors. The particular
detector whose NEFD is shown in Figure 2.6 falls within the best populated (tallest) bin in all three weather conditions. Repeating these calculations for AzTEC on ASTE at $\tau_{220} = 0.09$, 0.13, and 0.16 (which correspond to the three JCMT measurements at $\tau_{225} = 0.11$, 0.16, and 0.20 if we assume the same total optical loading on the detectors) gives the distribution of bolometer NEFDs shown in the right panel of Figure 2.7.

### 2.4.2 Mapping Speed and Instrument Sensitivity

The best indicator of future performance and capability for an array receiver is the instrument mapping speed. Mapping speed is a metric that can be summed linearly and simultaneously accounts for the variations in detector sensitivities, the
effectiveness of the atmospheric cleaning algorithm, the individual optical efficiencies achieved by each detector, and most importantly, the residual correlations between detectors in the array. We calculate the empirical mapping speed for our raster-scanned maps as

$$M_{em} = \frac{\Omega_{pix}}{N_{pix}} \sum_{i=1}^{N_{pix}} \frac{1}{\sigma_i^2 t_i},$$

(2.8)

where $\sigma_i$ represents the noise level of the $i^{th}$ pixel in a map with $N_{pix}$ pixels of solid angle $\Omega_{pix}$, and $t_i$ is the integration time spent on that pixel.

Point source mapping speeds achieved through raster-scanning of the JCMT05B observations of large blank-fields are plotted in Figure 2.8 (black data-points). Most overheads and mapping efficiencies are ignored, making these idealized speeds generally applicable to scanned AzTEC maps at any observatory by scaling the mapping speed values by the ratio of the telescope areas (assuming similar telescope efficiencies). For comparison, mapping speeds calculated from Lissajous-scan maps (Section 4.2.1) of the GOODS-S field with AzTEC on ASTE are shown in red. For the ASTE data, the x-axis represents the expected value of $\tau_{225}$ estimated from the measured value of $\tau_{220}$ using a scale factor of 1.22 (determined from Figure 2.3). These mapping speed estimates from the JCMT and ASTE are consistent with the expected scaling with telescope area.

It is generally favorable to apply a point source filter after the co-addition of multiple raster-scanned maps due to the benefits of cross-linking. To estimate effective mapping speeds of the individual observations presented in Figure 2.8, the $\sigma_i$ values are estimated as the unfiltered pixel noise scaled by the average reduction factor due to our optimum filter (Section 3.3.5) when applied to a co-added map.

Mapping speed is correlated to the atmospheric conditions in two ways: atmospheric loading (shot noise) and atmospheric stability. The latter gives rise to residual fluctuations that are inseparable from astronomical signals and lead to much of the scatter in the mapping speeds. While the high scatter in mapping speeds at the
Figure 2.8. Empirical point source mapping speeds for the AzTEC/JCMT system (black) and the AzTEC/ASTE system (red) as a function of atmospheric opacity. These mapping speeds were calculated according to Equation 2.8 and do not include overheads and mapping efficiencies that are specific to the observing strategy employed. See text for details.
lowest opacities may be due in part to errors in the opacity measurements, the fact that we see this with both JCMT and ASTE observations, where $\tau_{\text{eff}}$ is estimated with different instruments, suggests that this scatter could result from the failure to identify and remove some of the correlated signal in the best weather conditions. We can test this and possibly adjust our PCA cleaning algorithm to improve the correlated signal removal in the future.

Table 2.2 gives the expected and achieved noise performance of the instrument in a manner that allows one to compare ideal and achieved detector sensitivities and mapping speeds in terms of flux density. In the table, the column of “Projected” sensitivities indicates the sensitivity predicted from the bolometer model and the measured optical loading at the JCMT (Wilson et al., 2008). The columns of “Measured” sensitivities show the achieved sensitivities in the presence of atmospheric noise in three cases: 1) if “perfect” atmospheric noise subtraction were possible as measured by the 10 Hz value of the time-stream detector noise from Figure 2.6; 2) with the achieved atmospheric noise subtraction indicated by the thinner power spectral density (PSD) curves of Figure 2.6 and the point source response function (dash-dotted and dotted curves in that Figure); and 3) as inferred from empirical mapping speed estimates obtained with Equation 2.8. We use the following relationship between mapping speed and detector sensitivity $\hat{s}$ (in mJy$\sqrt{s}$) to calculate one where the other is known:

$$\text{MS} = \frac{3600N_{\text{det}}\Omega_b}{2\hat{s}^2}$$  \hspace{1cm} (2.9)

where $N_{\text{det}}$ is the number of working detectors and $\Omega_b = 0.10$ (0.28) arcmin$^2$ is the area under an 18$''$ (30$''$) FWHM 2-dimensional Gaussian. Equation 2.9 assumes the use of a simple beam-smoothing filter on maps. The factor of $2\hat{s}^2$ in the denominator represents the square of $\hat{s}_{\text{sm}} (= \sqrt{2}\hat{s})$, the appropriate sensitivity post smoothing.

The degradation of sensitivity and mapping speed between columns 3 and 4 is believed to be due to non-idealities such as residual bolometer-bolometer correlations
Table 2.2. Expected and achieved noise performance of AzTEC on the JCMT, ASTE, and LMT. “Projected” is the (white) time-stream power spectral density (PSD) prediction based on the bolometer model and optical loading. “Measured (white PSD)” is the noise level measured from calibrated raw time-stream PSDs at 10 Hz for $\tau_{225} = 0.11$ (i.e. from the thicker red curve of Figure 2.6) and is the median of all operational bolometers. “Measured (full PSD)” is the inferred sensitivity based on the full cleaned time-stream PSD at $\tau_{225} = 0.11$ (i.e. from the thinner red curve of Figure 2.6). The quoted sensitivity is calculated by the average of the PSD/2, weighted by the square of the point source response function shown in Figure 2.6. “Measured (map-space)” is the sensitivity inferred from mapping speeds estimated with Equation 2.8. Values given in bold are directly computed from AzTEC data. Values for the LMT are estimated by scaling the JCMT values according to telescope area as described in the text.

<table>
<thead>
<tr>
<th></th>
<th>Projected (model)</th>
<th>Measured (white PSD)</th>
<th>Measured (full PSD)</th>
<th>Measured (map-space)</th>
</tr>
</thead>
<tbody>
<tr>
<td>JCMT</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NEFD</td>
<td>10.0</td>
<td>8.78</td>
<td>12.2</td>
<td>27 mJy$/\sqrt{\text{s}}$</td>
</tr>
<tr>
<td>MS</td>
<td>184</td>
<td>255</td>
<td>131</td>
<td>26.6 arcmin$^2$/mJy$^{-2}$/hr$^{-1}$</td>
</tr>
<tr>
<td>ASTE</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NEFD</td>
<td>23</td>
<td>25.8</td>
<td>38.4</td>
<td>71 mJy$/\sqrt{\text{s}}$</td>
</tr>
<tr>
<td>MS</td>
<td>82</td>
<td>82</td>
<td>37</td>
<td>10.9 arcmin$^2$/mJy$^{-2}$/hr$^{-1}$</td>
</tr>
<tr>
<td>LMT</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NEFD</td>
<td>1.2</td>
<td>1.1</td>
<td>1.5</td>
<td>3.3 mJy$/\sqrt{\text{s}}$</td>
</tr>
<tr>
<td>MS</td>
<td>1500</td>
<td>2100</td>
<td>1100</td>
<td>220 arcmin$^2$/mJy$^{-2}$/hr$^{-1}$</td>
</tr>
</tbody>
</table>

which are not apparent from the time-stream PSDs. We emphasize that column 4 of Table 2.2, or more generally, Figure 2.8, properly scaled by telescope area, is the most accurate reference for planning observations with AzTEC. The values given in Table 2.2 are only meant to be illustrative of where the losses in sensitivity occur when beginning projections with raw detector sensitivities.

2.5 AzTEC on the Large Millimeter Telescope

AzTEC will be delivered to the 50-m LMT in late 2009, where it will serve as a first-light instrument at 2.1 mm, and then operate as a facility instrument for general use in all three of its wavebands. Projected detector sensitivities and mapping speeds for AzTEC at 1.1 mm on the LMT are shown in Table 2.2. These values
are determined by scaling the projected and measured values from AzTEC on the JCMT according to telescope area assuming an effective LMT mirror diameter of 43-m as (very conservatively) truncated by AzTEC’s Lyot stop. The mapping speed estimate for the LMT from column 4 is expected to be somewhat higher: the smaller field-of-view of AzTEC on the LMT (∼1.5′) results in stronger bolometer-bolometer correlations from the atmospheric loading which will be more easily identified and removed with our PCA cleaning algorithm.

AzTEC on the 50-m LMT will be comparable in terms of mapping speed to the upcoming SCUBA2 camera (850 µm) on the 15-m JCMT and will thus be competitive in mapping large areas of sky for submm/mm-galaxy (SMG) surveys. The major benefit of AzTEC/LMT over SCUBA2/JCMT is the improvement in angular resolution: 5″ FWHM at 1.1 mm versus 15″ at 850 µm. AzTEC on the LMT will have a much lower confusion-limit than SCUBA2 on the JCMT and will thus be sensitive to much fainter SMGs with intrinsic far-infrared luminosities of $L_{\text{FIR}} \sim 10^{11} \, L_\odot$ and star-formation rates of SFR $\sim 10 - 50 \, M_\odot/\text{yr}$. The high resolution afforded by the LMT will also give $\approx 1″$ positional accuracy for the mm-detected sources and will allow for the first time the determination of multi-wavelength counterparts to SMGs without the need for follow-up radio or submm/mm interferometry.
CHAPTER 3
AZTEC MILLIMETER SURVEY OF THE COSMOS FIELD

3.1 Introduction

A decade after the discovery of a population of extremely luminous, high-redshift dust-obscured galaxies detected by their submillimeter (submm) and millimeter (mm) wavelength emission (Smail et al., 1997; Hughes et al., 1998; Barger et al., 1998), over 300 submm/mm-galaxies (hereafter SMGs) have been detected with signal to noise ratio $S/N \geq 4$ in blank-field surveys (e.g. Borys et al., 2003; Greve et al., 2004, 2008; Laurent et al., 2005; Coppin et al., 2006) and in surveys towards moderate-redshift clusters designed to probe the faintest SMGs via lensing (e.g. Smail et al., 1998, 2002; Chapman et al., 2002). Their high far-infrared (FIR) luminosities ($L_{\text{FIR}} \sim 10^{12-13} L_{\odot}$) and inferred star-formation rates ($\text{SFR} \gg 100 \text{ M}_{\odot}/\text{yr}$; Smail et al., 1997; Hughes et al., 1998; Barger et al., 1998) suggest that these galaxies are high-redshift analogs to the local ultra-luminous infrared galaxy (ULIRG) population (Sanders & Mirabel, 1996), and that they may be the progenitors of the massive elliptical population observed locally.

Until recently, the relatively modest mapping speeds of the Submillimeter Common User Bolometer Array (SCUBA, 850 µm; Holland et al., 1999) on the 15-m James Clerk Maxwell Telescope (JCMT), MAMBO (1.2 mm; Kreysa et al., 1998) on the Institut de Radio Astronomie Millimetrique (IRAM) 30-m telescope and Bolocam (1.1 mm; Glenn et al., 1998; Haig et al., 2004) on the 10-m Caltech Submillimeter Observatory (CSO), have restricted SMG surveys to $< 300$ arcmin$^2$ in size, limiting our understanding of the brightest, rarest SMGs and resulting in wide variations in
the derived number counts as a result of small number statistics and cosmic variance
(e.g. Chapman et al., 2002; Smail et al., 2002; Scott et al., 2002; Borys et al., 2003). With new emphasis on large (> 300 arcmin$^2$) submm/mm blank-field surveys (Greve et al., 2004, 2008; Laurent et al., 2005; Mortier et al., 2005; Bertoldi et al., 2007), an accurate characterization of the bright-end of the SMG number counts and the mean properties of the SMG population is now becoming possible (e.g. Coppin et al., 2006).

We surveyed a 0.15 deg$^2$ region within the COSMOS field (Scoville et al., 2007b) with uniform sensitivity at 1.1 mm with the AzTEC camera (Wilson et al., 2008) on the JCMT. The AzTEC survey field (Figures 3.1 and 3.2) is centered on a prominent large-scale structure as traced by the optical/IR galaxy density (Scoville et al., 2007a), including a massive galaxy cluster at $z = 0.73$ (Guzzo et al., 2007). This AzTEC map has no overlap with the MAMBO/COSMOS survey (Bertoldi et al., 2007) and only a small amount of overlap with the larger, shallower Bolocam survey (J. Aguirre, private communication). The MAMBO and Bolocam surveys cover the same low galaxy density region of the COSMOS field, whilst our new AzTEC observations are designed to examine the impact of massive large-scale foreground structures on SMG surveys in order to provide a measure of the importance of cosmic variance in the observed source density at mm wavelengths.

In this Chapter we present the AzTEC 1.1 mm survey of the COSMOS field, including the data reduction, source catalog, and number counts. The JCMT observations, pointing, and calibration strategy are described in Section 3.2. A detailed description of the data reduction algorithm is given in Section 3.3. In Section 3.4, we present the AzTEC map and source catalog, followed by a discussion of simulations used to determine flux-boosting, false detections, completeness, and source positional uncertainty in the map in Section 3.5. A preliminary comparison of the mm-sources to the radio and MIPS 24 μm populations is made in Section 3.6, and we
discuss the contribution of AzTEC sources to the Cosmic Infrared Background (CIB) in Section 3.7.

The large number of bright SMGs identified in our COSMOS survey strongly suggests a bias in the number density introduced by the known large-scale structure that is present in the map. A detailed treatment of this analysis is discussed in Austermann et al. (2009b), and we summarize these results in Section 3.8. The multi-wavelength imaging data from the *Hubble Space Telescope* (*HST*), *Spitzer* IRAC and MIPS, as well as deep radio imaging from the Very Large Array (VLA) is particularly valuable for identifying and studying the nature of the SMGs identified by AzTEC. We present a complete study of the multi-wavelength properties of the 15 brightest SMGs detected in the COSMOS field and imaged with the Submillimeter Array (SMA) in Younger et al. (2007, 2009), and we summarize these results in Section 3.9. We conclude with a summary of the results from this AzTEC survey of the COSMOS field in Section 3.10.

We assume a flat $\Lambda$CDM cosmology with $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 73$ km s$^{-1}$ Mpc$^{-1}$ throughout.

### 3.2 Observations

We selected a 0.3 deg$^2$ region in the northwest quadrant of the COSMOS field for mm-imaging with AzTEC. Only the central area of 0.15 deg$^2$, with uniform noise, is discussed in this Chapter. The observations were carried out at the JCMT in November and December 2005. A total of 34 hours of telescope time (excluding pointing and calibration overheads) was devoted to this survey.

Details of the AzTEC instrument specifications, performance, and calibration method at the JCMT are described in Chapter 2 and Wilson et al. (2008) and are briefly summarized here. The array field-of-view is roughly circular with a diameter of 5.0'. During the JCMT observing campaign, 107 out of the 144 detectors were op-
Figure 3.1. The AzTEC/COSMOS map and source candidates. *Top*: The galaxy density map from Scoville et al. (2007a), with the boundaries of the AzTEC, Bolocam, and MAMBO mm-wavelength surveys within the COSMOS field indicated. The location of the $z = 0.73$ cluster environment is identified by the dashed circle. *Bottom*: The AzTEC/COSMOS map with $\geq 3.5\sigma$ source candidates identified by circles with diameters equal to twice the AzTEC FWHM on the JCMT. The map has been trimmed to the “75% coverage region” and has an average noise level of 1.3 mJy/beam and an area of 0.15 deg$^2$. The signal map has been Wiener-filtered for optimal identification of sources as described in Section 3.3.5.
The point spread function (PSF) of the detectors is determined from beam-map observations on bright point sources and is well described by a 2-dimensional Gaussian, with a beam full width at half maximum (FWHM) of $17'' \pm 1''$ in azimuth and $18'' \pm 1''$ in elevation.

The COSMOS data-set consists of 34 individual raster-scan observations, each centered at a right ascension and declination of $(\text{RA}, \text{Dec})=(10^h 00^m 00.00^s, +02^\circ 36' 00.0'' )$. The observations were taken in unchopped raster-scan mode by sweeping the telescope in elevation, taking a small step of $10''$ in azimuth, then sweeping back in the opposite direction, moving only the primary dish. This pattern is repeated until the entire field has been mapped. The small step size ($\approx 1/2$ the beam FWHM) and chosen scan speeds result in a Nyquist-sampled sky with extremely uniform coverage for each individual observation.

The first half of the observations were taken early in the JCMT observing run, while scanning strategies were still being optimized. For these observations, we imaged a $25 \times 25$ arcmin$^2$ region using a scan speed of $90''$/s. From diagnostic tests of these early AzTEC/JCMT observations, we determined that a faster scan speed of $150''$/s was optimal, since scanning the camera faster moves the point source response to higher temporal frequencies and away from the low-frequency atmospheric signal, improving the effectiveness of our cleaning algorithm (Section 2.4.1). The time necessary to turn the telescope around between scans (i.e. reverse direction) is constant and independent of scan speed. Therefore, to maintain observational efficiency, we expanded the survey region to $30 \times 30$ arcmin$^2$ for the later observations.

Since the array orientation is fixed in azimuth and elevation, the scan angle in the RA–Dec plane for a raster-scan map continuously changes due to sky rotation. When combining several observations with different scan angles into a single map, we obtain excellent cross-linking that suppresses scan-synchronous systematic noise.
in the maps. We chose to scan in the elevation direction rather than in azimuth to avoid vibrational noise from the telescope dome motion (Section 2.2.1).

The zenith opacity at 225 GHz, $\tau_{225}$, was recorded every 10 minutes by the CSO tau monitor. For the AzTEC/COSMOS observations, the effective opacity, $\tau_{225} \cdot A$, where $A$ is the airmass, ranged from 0.07 to 0.27 with an average value of 0.15. The empirical mapping speed (excluding overheads) derived from the individual COSMOS observations ranges from 8 to 34 arcmin$^2$mJy$^{-2}$ hr$^{-1}$ and is a strong function of $\tau_{225} \cdot A$ (Section 2.4.2, Figure 2.8), suggesting that the noise in each individual observation is dominated by residual atmosphere that is not removed in the cleaning process. We discuss the details of atmosphere removal and optimal filtering in the Section 3.3.

3.2.1 Pointing

Jiggle-map observations (see Wilson et al., 2008) of J1058+015, a variable quasi-stellar object with a mean flux density of 2.8 Jy, were made approximately every two hours in order to generate small corrections to the JCMT’s pointing model. These pointing observations bracket the science observations so that we can measure the absolute pointing offset between the telescope boresight and the reference bolometer and correct for slow drifts in the residuals to the telescope pointing model. We fit a 2-dimensional Gaussian to the point source image, and the best-fit location of the peak signal gives the boresight offset. These corrections were not made in real-time. Instead, a correction based on a linear interpolation of the measured pointing offsets was applied to each observation $ex post facto$. In Section 3.6.2 we demonstrate that the resulting absolute pointing uncertainty of the AzTEC map is $< 2''$.

3.2.2 Flux Calibration

The AzTEC calibration has been derived from beam-map observations of Uranus, which had a predicted flux density of 41–52 Jy at 1.1 mm during the JCMT observing run. We fit a 2-dimensional Gaussian to the PSF of each detector to determine the flux
Figure 3.2. The weight map for the AzTEC/COSMOS survey. The contours show curves of constant noise and are 1.4, 1.8, and 2.5 mJy/beam from the innermost to the outermost contour. The thick, innermost contour indicates the 0.15 deg² “75% coverage region” where the signal map is trimmed to provide very uniform coverage in the region where the analysis in this paper is carried out. The noise levels in this central region of the map range from 1.2 to 1.4 mJy/beam.
conversion factor (FCF) from optical loading (in Watts) to source flux (in Jy/beam). Beam-maps were taken once per night. The extinction- and responsivity-corrected FCF for each detector did not vary greatly over the entire observing run. We use an average FCF for each bolometer determined from all Uranus beam-maps taken at the JCMT. The total error of $5 - 13\%$ on the calibrated signals includes the standard deviation of the measured FCFs plus errors from the extinction and responsivity corrections (Section 2.3.3.1). This value does not include the 5\% absolute uncertainty in the flux density of Uranus (Griffin & Orton, 1993). The data are calibrated after atmosphere removal and before combining the time-stream signals from all bolometers into a single map.

### 3.3 Data Reduction

The AzTEC/COSMOS data-set is reduced using the publicly available AzTEC Data Reduction Pipeline V1.0 written in IDL and developed by AzTEC instrument team members at the University of Massachusetts, Amherst. V1.0 has been optimized for the identification of point sources in blank-field extragalactic surveys. The 34 individual raster-scan observations that comprise the AzTEC/COSMOS data-set are ultimately combined to produce four data products: 1) a co-added signal map; 2) a corresponding weight map; 3) a set of noise maps which are representative of the noise in the co-added signal map; and 4) a representation of the instrument point source response, post-cleaning and filtering. We describe the techniques for creating these data products from raw AzTEC data in detail in this section.

The raw data-file for each raster-scan observation is composed of bolometer signals, telescope pointing signals, and environmental signals — all stored as a function of time and referred to hereafter as “time-stream” data. Detector signals are sampled at a rate of 64 Hz and all germane environmental signals are interpolated to this sampling rate in the analysis. In the description below, a “scan” is defined as a single constant-
velocity and constant-elevation pass of the telescope from one side of the field to the other. We do not use the data recorded as the telescope is strongly accelerating at the ends of the scans (during the turn-around), where the accuracy of the pointing signals is unknown and microphonic noise is more likely. Given the field size and scan velocities used for the AzTEC/COSMOS survey, this results in a loss of $22 - 34\%$ of the on-source observing time.

3.3.1 Despiking

Prior to atmosphere removal, the data are inspected for cosmic ray events and instrumental glitches, both of which register as “spikes” in the raw time-stream data. Spikes in the AzTEC data occur at a rate of $\sim 40 \text{ hr}^{-1}$, each usually confined to a single detector, and with amplitudes that vary widely from 30 mJy to 550 Jy. Spikes are defined in our automated spike identification and removal procedure as any instance where a detector signal jumps by a user-defined threshold (typically $> 7\sigma$ or $< 7\sigma$) between adjacent time samples. Generally, such jumps in detector output cannot be of astronomical origin as the continuous nature of the beam and the scanning strategy ensure a smoother signal. Spikes are located recursively, thus allowing for pairs of spikes with high dynamic range to be identified independently. A spike decay length (the time necessary for the spike signal to drop below the baseline noise level), is calculated based on the spike amplitude and a conservative estimate of the detector time constant. Adjacent samples are flagged accordingly, with a minimum of 12 (6) samples flagged after (before) the spike. Flagged data samples are not included in the map-making process. For the AzTEC/COSMOS data-set, flagged samples due to spikes account for $< 0.1\%$ of the total time-stream data.

Since the matrix operations in our atmosphere removal technique require that all bolometers have the same number of time-stream samples, we cannot simply discard the flagged samples. Large spikes can affect upwards of $\sim 20$ adjacent time samples.
for a single detector and de-correlate that detector’s time-stream from the remainder of the array. Unaccounted for, this would reduce the efficacy of the atmospheric cleaning technique and so we replace each set of flagged samples with the sum of two components: 1) Gaussian noise with variance equal to the variance of that detector’s time-stream from nearby unflagged samples; and 2) an appropriately scaled baseline calculated from the mean time-stream for all unaffected detectors. In this manner, the detector-detector covariance matrix is minimally affected and, more importantly, the inclusion of noise ensures that excess weight is not given to the synthetic time-stream samples. These simulated data are used only in the atmosphere removal process; all flagged samples are discarded when making the actual map.

3.3.2 Atmosphere Removal

The signal due to the fluctuating atmosphere dominates the background SMG population by three orders of magnitude. For the AzTEC/COSMOS data-set and other blank-field surveys we adopt an adaptive principal component analysis (PCA) technique similar to that described by Laurent et al. (2005) to remove, or “clean” the correlated sky noise from the time-stream data. Faint point sources are, in general, not correlated between detectors in the array while the atmosphere is correlated on all spatial scales of interest. The adaptive PCA technique uses the degree of correlations to distinguish between the two.

Cleaning is accomplished on a scan by scan basis. The basic adaptive PCA cleaning process is as follows: a covariance matrix is constructed from the $N_{\text{bolo}} \times N_{\text{time}}$ despiked time-stream data for each scan and then eigenvalue decomposed. The relative amplitudes of the resulting eigenvalues are representative of the degree of correlation of the detector signals for the mode described by the respective eigenvector. Since fundamental detector noise and faint point sources are not correlated amongst multiple detectors, they will not lie preferentially in modes having large eigenvalues. The
atmosphere, fluctuations in the detector bias chain, and other common-mode signals dominate the correlated variance with their power in modes with large eigenvalues. The technique, then, is to identify and project out modes with the largest eigenvalues.

The choice of which modes to remove from the data is somewhat arbitrary. Empirically we have found the following to work well. First, the mean and standard deviation in the base-10 logarithm of the eigenvalue distribution is determined, then large eigenvalues that are $> 2.5\sigma$ from the mean are cut. This process is repeated until no $> 2.5\sigma$ outliers exist. An example of the time-stream data and power spectral density (PSD) before and after PCA cleaning is shown in Figure 3.3. The significant decrease in the power at low frequencies demonstrates how this adaptive PCA cleaning technique effectively removes much of the atmospheric signal.

There are two consequences of the adaptive PCA technique that must be addressed. First, since faint point sources have power at low spatial frequencies, there is no way to completely decouple the atmosphere from the point source signal. We therefore expect some attenuation of point sources in the resulting map. Secondly, PCA cleaning AC-couples the time-stream signal, leaving the mean of the samples for each bolometer in a single scan equal to zero.

We trace the effects of PCA cleaning on the point source response profile and its amplitude to generate the point source kernel, which we use later in the analysis to optimally filter the map and correct for the attenuation. Since the degree of attenuation varies according to the conditions of the atmosphere for a given observation, we create a point source kernel for each observation separately. The procedure is as follows: 1) each scan of an observation is cleaned according to the prescription given above, saving the set of eigenvalues and eigenvectors for later use; 2) an analogous, synthetic time-stream is created using the pointing signals to make a fake “observation” of a 1 Jy point source centered in an otherwise empty and noiseless field. The flux of the synthetic point source is arbitrary – we only need to determine the
Figure 3.3. The raw and cleaned bolometer time-stream signals and power spectral densities (PSDs). *Top left:* The raw time-stream signals for a sample bolometer during a single scan. *Bottom left:* The same time-stream signals after PCA cleaning. Note the factor of 20 reduction in the noise level post-cleaning. *Right:* The PSD of the same scan, before (black) and after (red) PCA cleaning, demonstrating the reduction of low-frequency signal. The PSD of the post-cleaned data is truncated at 16 Hz due to a digital low-pass filter that is applied to the data before PCA cleaning.
factor of attenuation and the effect that PCA cleaning has on the shape of the point source response; 3) the dominant eigenvectors identified in 1) are projected out from the synthetic data; and 4) a map is made from this cleaned, synthetic data. The resulting image is the point source kernel, and it has the same shape and attenuation as a point source in the cleaned signal map for a given observation. This is true only if the real sources in the time-stream signal do not significantly affect the PCA cleaning, and if the kernel does not vary greatly in shape and attenuation across the whole field. The standard deviation and spatial PSD of an individual signal map is comparable to that in a jackknifed noise realization of that map (see Section 3.3.4), which suggests that the former must be true. We have tested the latter assumption by placing the synthetic 1 Jy point source at different locations in the field. We find that the shape of the kernel is not affected by its location, and the measured peak of the PCA-cleaned kernel varies by less than 2% over the entire field.

In Figure 3.4, we show a cut in elevation through the synthetic point source for one of the observations, before and after PCA cleaning. This demonstrates the attenuation that a real source experiences from the atmosphere removal process. In this case, the sources will be attenuated by 17.8% due to PCA cleaning. This also shows how the cleaning affects the shape of point sources. The central peak is now flanked with negative side-lobes and has a small negative baseline that extends across the map, making the mean of the point source response equal to zero.

3.3.3 Raw Signal Maps

We cast each of the 34 individual raster-scan observations into map-space prior to co-adding them into a single map. Hereafter, we will refer to any maps that are made for a single observation as an “individual” map. To ensure that all of these individual maps will have the same coordinate grid, we convert the time-stream pointing signals into offset positions relative to the map center at (RA, Dec) =
Figure 3.4. A cut in elevation of the point source kernel for an individual observation. The black curve shows the effective PSF (once all bolometer signals are combined) before PCA cleaning. The red curve shows the resulting point source response function after the synthetic source has been PCA cleaned in the same manner as the real time-stream signals.
(10^8m00.00^s, +02°36′00.0″). These pointing signals are then binned into 2 × 2 arcsec^2 pixels, creating the underlying coordinate grid for the map. We chose 2″ pixelization in order to avoid significant dilution of the peak signal from point sources while maintaining a statistically sufficient number of samples (≥ 9) in each pixel. The map value for pixel \( j \) in observation \( i \), \( S_{i,j} \), is calculated from the weighted average of all samples whose central pointing falls within the pixel boundary, combining the samples from all bolometers simultaneously and excluding any samples flagged in the despiking process. The weight of each sample is taken to be the inverse variance of the respective detector’s samples in the parent scan. This weighting scheme is only suitable for cases where the source signal is consistent with noise for a single scan observation, which is true for the entire AzTEC/COSMOS data-set.

For each individual COSMOS map, \( S_i \), we also make the corresponding individual “weight map”, \( W_i \), by adding in quadrature the weights of all bolometer samples that contribute to a pixel. As the flux assigned to a pixel is a weighted average of these samples, the weight of a pixel is proportional to \( \sigma_i^{-2} \) of the flux estimate. The proportionality constant may differ from unity because all samples contributing to a pixel may not be completely independent, for instance due to detector-detector correlations resulting from imperfect atmosphere removal. However, because the scan strategy and analysis technique are essentially identical for all observations, we expect on average that this proportionality constant is identical over the 34 individual observations and over all pixels of an individual map. As noted before we also make an image of the point source kernel, \( K_i \), for each individual observation.

We combine all individual COSMOS observations into a single image by computing for each pixel the weighted average over the individual maps:

\[
S = \frac{\sum_{i=1}^{34} W_i S_i}{\sum_{i=1}^{34} W_i}.
\] (3.1)
As with each of the individual observations, we also produce the weight map, $W$, corresponding to this co-added signal map and an averaged point source kernel, $K$.

### 3.3.4 Noise Maps

With the construction of $S$, $W$, and $K$ we have most of the raw ingredients for making the final map. In order to optimally filter $S$, however, we must construct an estimate of the noise in $S$. We do this by generating “jackknifed” noise realizations for each COSMOS observation. This is accomplished by multiplying each scan in the cleaned time-stream data by $\pm 1$ (chosen at random) before the map-making process. This removes the sources, both resolved and confused, from the bolometers’ signals while preserving the noise properties in the individual scans. We then combine jackknifed noise realizations made from each of the 34 observations in the same manner as for the real individual maps to create a single co-added noise map, $N$. We choose to jackknife on single-scan scales to ensure a statistically significant number of elements (there are $150 - 200$ scans per observation) and to ensure nearly equal weightings in the positive and negative components while conserving low-frequency components (each scan is $> 10$ sec and $\geq 25'$ in length). This was tested against the more traditional approach to jackknifing, where half of the individual signal maps are multiplied by a factor of $-1$ before combining the full data-set, which gave consistent results.

For the AzTEC/COSMOS data-set we create five jackknifed noise realizations for each of the 34 COSMOS observations. To verify that these noise realizations are consistent with the noise in the individual signal maps, we compare the standard deviation and the spatial PSD of the noise realizations to those in the raw individual signal maps directly. This test is valid since the contribution from real sources in the individual signal map for a single observation is negligible. We find that the difference between the standard deviations of the individual signal maps and their jackknifed
noise realizations is less than 0.6% for every observation. We use random combinations of these noise realizations, one representing each individual observation at a time, to generate a total of 100 co-added noise maps for the field – each a realization of the underlying noise in the co-added signal map, $S$. As described below, these noise maps are used in creating the optimal point source filter for the co-added signal map, and as the underlying noise in synthetic source maps.

3.3.5 Optimal Filtering

At this stage in the analysis, pixel-to-pixel signal variations stand out prominently in the co-added signal map. These variations are not of astronomical origin as the pixel size, $2''$, is much smaller than the AzTEC beam. One way to filter out such features is to convolve the signal map with our co-added point source kernel, $K$. The resulting map must then be scaled to account for attenuation of the kernel from PCA cleaning. If the noise covariance matrix of the signal map was diagonal, that is, if the errors in the pixel values were independent, then this two-step procedure would be mathematically equivalent to a fitting procedure: that of shifting the center of $K$ to the center of each pixel in $S$ and fitting it to the signal map to find a best-fit amplitude. The $K$-convolved scaled map is equivalent to a map of those best-fit amplitudes. This analogy to fitting is useful since it provides guidance on generalizing the filter/convolution procedure and on propagating the error/weight map.

The presence of excess long-wavelength noise in the Fourier transform of noise maps is clear evidence of pixel-pixel noise correlations. We de-weight these long-wavelength modes by filtering the signal map with the inverse of the square root of the PSD, averaged over the 100 noise maps. This filter makes the noise power flat with frequency or, equivalently, removes pixel-pixel correlations in the filtered map. This “whitening” filter is applied to both the signal map and the point source kernel. At this point, a linear convolution of the two is the same as fitting the whitened
kernel to the whitened map assuming a uniform uncertainty for all pixel values. Such a fit/convolution is equivalent to the conventional “optimal filtering” procedure used by other groups (e.g. Laurent et al., 2005), but we follow the fit analogy to completion by including non-uniform coverage as non-constant error values in the fit.

The proper accounting of non-uniform coverage is important for two reasons. First, implicit to such map-making and filtering procedures is the assumption that the sky as seen by AzTEC can be described by a set of discrete points – the centers of the map pixels. For large pixel sizes, this assumption is invalid and results in fluxes (e.g. from point sources) being smoothed out. Therefore, we would like to explore the use of small pixel sizes. While raster-scan maps made with AzTEC have rather uniform coverage on beam sized scales, the coverage has non-uniformity on small scales like 2″. Some groups (e.g. Coppin et al., 2006) seek an “optimal” pixel size that is small enough to avoid flux smoothing effects and large enough for the coverage variations between pixels to be negligible. But such an optimum may not exist. By including variations in coverage as variable error values in a fitting procedure, we circumvent having a lower limit to the pixel size, save for practical CPU time considerations. Empirically, we have found that pixel sizes below 3″ yield essentially the same results in terms of fluxes and sources recovered in AzTEC/JCMT maps.

Second, the error values are formed from our estimate of the uncertainty of each pixel value. Thus, our estimate of the sky coverage of each pixel is correctly propagated through the analysis, resulting in a new weight map that represents the formal weight in the best-fit amplitudes at each pixel. In summary, the optimal filter consists of: 1) finding the best-fit amplitude from fitting a whitened point source kernel to every pixel of a whitened signal map with proper account for the uncertainty of each pixel value; and 2) propagating the weights to yield a new weight map representing the uncertainty in the best-fit amplitude at each pixel. The signal map times the square root of this weight map represents the $S/N$ for each pixel.
The above filtering procedure is implemented with linear convolutions, made quicker by the use of fast Fourier transforms. In the optimal filter, a rotationally symmetrized version of the point source kernel is used. This is a better approximation to point sources over the entire map than the raw kernel averaged over individual observations, which has scan-oriented artifacts that are relevant only to a particular central region of the map. We also make use of noise maps to avoid lengthy calculations and to find an absolute normalization factor for values in the final weight map. The mathematical formulation of this optimal filter and the details of its implementation will be presented in a future work.

3.4 Source Catalog

The AzTEC/COSMOS signal map and its weight map are shown in Figures 3.1 and 3.2. The signal map shown has been trimmed such that only pixels with weights \( \geq 75\% \) of the map’s characteristic (roughly the maximum) weight are included. This results in a nearly circular map with total area \( 0.15 \text{ deg}^2 \) and very uniform noise across the map, ranging from 1.2 mJy/beam in the center to 1.4 mJy/beam at the edges of the map. Unless otherwise stated, we limit our analysis to this “75% uniform coverage region”.

Figure 3.5 shows the histogram of the pixel flux density values in the map. The averaged histogram of pixel values from the filtered noise maps, which is well-fit by a Gaussian with \( \sigma = 1.3 \text{ mJy/beam} \), is also shown for comparison. There is a clear excess of positive flux pixels in the signal map compared to the noise maps, indicating the presence of both bright and confused sources. The presence of real sources in the map also produces an excess of hot negative flux pixels over that expected from Gaussian random noise due to the fact that our map is AC-coupled with a mean of zero. Each source in the map is a scaled version of the point source kernel and contributes excess negative signal due to the negative side-lobes surrounding the
Figure 3.5. Histogram of fluxes from the signal map (red) and the average histogram of fluxes from the noise maps (black) with the best-fit Gaussian over-plotted. A clear distortion of the map pixel flux values from that expected from noise is seen in the signal map due to the presence of real sources.

central peak (see Figure 3.4). Real sources change the distribution of flux values in the map from that expected of pure Gaussian noise by skewing the flux distribution (making it very non-Gaussian), broadening the distribution, and shifting the peak to $< 0$.

Bright source candidates are identified in the $S/N$ map as local maxima within an $18''$ window above a $S/N$ threshold of 3.5. We find that reducing the “single-source” window from $18''$ to $4''$ results in the same number of source detections. While none of these sources are visually extended, it is possible that some of our individually detected sources consist of multiple components blended together due to
the large beam of the instrument. We could attempt to “deblend” detected sources by fitting them to a combination of two (or more) point source kernels, but this is precluded by the low $S/N$ of the detections that makes it difficult to distinguish between a single source versus multiple blended sources. Sub-pixel centroiding of the source coordinates is calculated by weighting the pixel positions within a $9''$ radius of the brightest pixel by the flux squared. This method results in a list of 50 source candidates with $S/N \geq 3.5$, which are listed in Tables 3.1 and 3.2. The measured flux density for a source is given by the map value at its peak, and the error on the flux density by the noise in that pixel. Note that the optimal filter correctly scales the flux values in the map to account for the flux attenuation arising from PCA cleaning. The “deboosted” 1.1 mm fluxes for the AzTEC/COSMOS source candidates listed in Tables 3.1 and 3.2 represent the maximum likelihood flux density using the semi-Bayesian approach outlined in Section 3.5.1.

We find a large number of very bright, high-significance sources in our map, 9 of which have intrinsic fluxes $\geq 5$ mJy. Assuming a modified blackbody spectral energy distribution (SED) with dust temperature $T_d = 40$ K and emissivity $\beta = 1.6$, these very bright AzTEC galaxies have $L_{\text{FIR}} > 6.0 \times 10^{12}$ $L_\odot$. Assuming that all of the bolometric output arises from star-formation and the relationship between SFR and $L_{\text{FIR}}$ for starburst galaxies from Kennicutt (1998), this implies SFRs $> 1100$ $M_\odot$/yr. The fifteen brightest SMGs in this field have been followed-up with interferometric imaging at 890 $\mu$m using the Submillimeter Array (SMA; Younger et al., 2007, 2009), and all are detected with $S/N \geq 4$ (see Table 3.1), confirming the reality of these sources. A summary of the results from this SMA survey of the bright AzTEC sources in this field is given in Section 3.9.

From the blank-field 1.1 mm number counts of Austermann et al. (2009a), we expect on average only 2 – 3 sources with intrinsic flux density $\geq 5$ mJy in a blank, unbiased field of this size, compared to the 9 discovered in the AzTEC/COSMOS map.
Our map deliberately surveys a biased portion of the COSMOS field (Figure 3.1) by being centered on prominent large-scale structure as traced by the galaxy density map of Scoville et al. (2007a). In Section 3.8, we summarize the analysis of Austermann et al. (2009b), where we have carried out a number of tests to quantify the correlation of the AzTEC sources with the projected galaxy over-density and weak-lensing mass maps.

### 3.5 Simulations

With the machinery described in Section 3.3 in place, it is straightforward to determine various characteristics of our signal map and our source identification process via Monte Carlo simulations. We generate synthetic source maps by populating our synthetic noise maps with point source kernel-shaped sources. Depending on the goal of the simulation, sources of a given flux are randomly placed into the signal or noise map one at a time, or entire populations of sources drawn from a parametrized number density distribution may be randomly distributed (spatially) in a noise map. When appropriate we determine characteristics of our survey with the former method in order to avoid biasing our results with the (weak) prior of the input source distribution.

#### 3.5.1 Flux Deboosting

Sources with low $S/N$ are detected at fluxes systematically higher than their intrinsic flux density when the source population increases in number with decreasing flux. This well known but subtle effect (e.g. Hogg & Turner, 1998) becomes important when there are far more faint sources, dimmer than the detection flux limit, than there are brighter sources. In this instance it becomes more likely that the numerous dim sources are boosted high by noise than the rarer bright sources are boosted to lower fluxes. This is particularly significant in surveys of SMGs, where detections are almost
Table 3.1. AzTEC/COSMOS source candidates detected with $S/N \geq 4$. Only two are expected to be false positives. The columns give: 1) AzTEC identification (SMA identification); 2) $S/N$ of the detection in the AzTEC map; 3) measured 1.1 mm flux density and error; 4) deboosted flux density and 68.3% confidence interval (Section 3.5.1); and 5) 890 $\mu$m flux density and error (Younger et al., 2007, 2009).

<table>
<thead>
<tr>
<th>AzTEC ID</th>
<th>(SMA ID)</th>
<th>$S/N$</th>
<th>$S_{1.1\text{mm}}$ (meas.) (mJy)</th>
<th>$S_{1.1\text{mm}}$ (deboost.) (mJy)</th>
<th>$S_{890\mu\text{m}}$ (mJy)</th>
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<td>(AzTEC2)$^{a,b}$</td>
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</table>

Notes: a) Sources have been detected with Bolocam (J. Aguirre, private communication); b) AzTEC sources with candidate MIPS 24 $\mu$m counterparts (Section 3.6.3); c) AzTEC sources with candidate radio counterparts (Section 3.6.2).
Table 3.2. AzTEC/COSMOS source candidates detected with $3.5 \leq S/N < 4$. These sources are less robust, and roughly half are expected to be false positives. The columns are the same as columns 1 – 4 in Table 3.1 (none of these sources have been targeted with the SMA).

<table>
<thead>
<tr>
<th>AzTEC ID</th>
<th>$S/N$</th>
<th>$S_{1.1\text{mm}}$ (meas.) (mJy)</th>
<th>$S_{1.1\text{mm}}$ (deboost.) (mJy)</th>
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Notes: a) – c) See comments in Table 3.1; d) These marginal detections are confirmed by Bolocam (Section 3.6.1). These sources have very ill-defined local maxima in their PFDs due to low $S/N$; the deboosted flux densities in these cases have been determined by the expectation value of the flux density from the PFD.
always at low $S/N$ ($< 10$) and the intrinsic population is known to have a very steep luminosity distribution (e.g. Scott et al., 2006, and references therein).

For each source candidate we calculate a posterior flux distribution (PFD) which describes the source’s intrinsic flux in terms of probabilities. The PFD is calculated through an implementation of Bayes theorem similar to that used by Coppin et al. (2005, 2006). For an individual source detected with measured flux density $S_m \pm \sigma_m$, the probability distribution for its intrinsic flux density $S_i$ is given by

$$p(S_i|S_m, \sigma_m) = \frac{p(S_i) \cdot p(S_m, \sigma_m|S_i)}{p(S_m, \sigma_m)}$$

(3.2)

where $p(S_i)$ is the prior distribution of flux densities, $p(S_m, \sigma_m|S_i)$ is the likelihood of observing the data, and $p(S_m, \sigma_m)$ is a normalizing constant. We assume a Gaussian noise distribution for the likelihood of observing the data, where

$$p(S_m, \sigma_m|S_i) = \frac{1}{(2\pi\sigma^2_m)^{1/2}} \cdot \exp\left(\frac{-(S_m - S_i)^2}{2\sigma^2_m}\right).$$

(3.3)

This assumption is justified by the Gaussian flux distribution observed in jackknifed noise maps (black histogram in Figure 3.5). We use a Schechter function of the form:

$$\frac{dN}{dS} = N' \left(\frac{S}{S'}\right)^{\alpha+1} \exp(-S/S')$$

(3.4)

for the prior of the number counts, which we use to simulate the flux distribution $p(S_i)$. We adopt the best-fit parameters to the SCUBA SHADES number counts (Coppin et al., 2006) scaled to 1.1 mm assuming an 850 $\mu$m–1100 $\mu$m spectral index of 2.7. The parameters for the Schechter function prior are $N' = 3200$ mJy$^{-1}$deg$^{-2}$, $S' = 1.6$ mJy, and $\alpha = -2.0$. While the PFDs will depend on the exact form of the source population, we have verified that maximum likelihood flux densities derived from this approach differ by less than 0.7 mJy (i.e. well within the photometric
error) for a variety of assumed models (e.g. single power-law, Schechter function) and a wide range of parameters as measured from previous SCUBA, Bolocam, and MAMBO SMG surveys (Coppin et al., 2006; Laurent et al., 2005; Greve et al., 2004, respectively).

We estimate the prior distribution of flux densities by generating 10,000 noiseless sky realizations, inserting sources with a uniform spatial distribution into a blank map with the source population described by Equation 3.4, where each source is described by the point source kernel. The pixel histogram of flux values from these sky maps gives an estimate of $p(S_i)$.

A plot of the PFD for a sample of the AzTEC source candidates is shown in Figure 3.6. These four sources represent the range of measured fluxes in the catalog and demonstrate how the PFD varies according to the strength of the detection. Strictly speaking, the PFD for a given source candidate depends on both its detected flux and noise, but this translates into a dependence on $S/N$ when the noise is uniform in the map, which is approximately true in this case. We calculate the deboosted flux density for each source by locating the local maximum value of the PFD. These values are listed in column 4 of Tables 3.1 and 3.2. The errors on the deboosted fluxes shown in these tables represent the 68.3% confidence interval.

Using the PFD, we can estimate the probability that each detected source candidate will be deboosted to < 0 mJy. Coppin et al. (2005, 2006) use these PFDs to exclude source candidates that have $\geq 5\%$ probability of deboosting to < 0 mJy as a way to limit the source list to candidates which have a higher probability of being real. While this may result in a source catalog with fewer false detections, it could exclude many real sources detected with low $S/N$ and reduce the completeness of the source catalog. Furthermore, while the deboosted flux densities derived from the PFDs are not very sensitive to the assumed source population used to generate the prior distribution, the number of source candidates that meet the null threshold
criterion is sensitive to the exact form of the prior. For these reasons, we choose to publish the entire list of $\geq 3.5\sigma$ source candidates with the stipulation that some fraction of this catalog (in particular, source candidates with $S/N < 4$) represent false detections, as addressed in Section 3.5.2.

### 3.5.2 False Detections

Traditionally, the number of false detections is given by the number of $> N\sigma$ peaks caused purely by noise and therefore appear at locations where there are no real sources. However, in surveys such as ours, where the confused signal is significant relative to the noise, every pixel in the map is affected by the presence of sources. Therefore, the definition of a false detection becomes rather arbitrary. Another complication is that source confusion will increase the number of positive and negative peaks in a map, beyond the number found in our synthetic noise realizations. A common practice is to count the number of negative peaks detected in the map with $> N\sigma$ significance. However, it is difficult to interpret that number, mainly because source confusion may augment the number of negative peaks differently from the number of positive peaks.

Therefore, we show in Figure 3.7 the number of “sources” detected when the usual source-finding algorithm is applied to our synthetic noise maps. These curves are proportional to the number of instances that a point with zero flux in a noiseless, beam-convolved map of the sky is detected above the given $S/N$ ratio (or flux density). Because nearly half the points on a noiseless, beam-convolved map would have sub-zero flux (due to the AC-coupling), the curves of Figure 3.7 give an upper limit to the number of such sub-zero points that would spuriously be called detections. Using this definition, the expected number of false detections for AzTEC/COSMOS sources with $S/N \geq 4$ (those listed in Table 3.1) is $\sim 2$. 
Figure 3.6. The posterior flux distribution (PFD) for a sample of four AzTEC source candidates, whose $S/N$ values are representative of the range observed in the entire source list. The dashed curve shows the Gaussian distribution assumed for the measured source flux distribution, $p(S_m, \sigma_m | S_i)$. The dotted curve is $p(S_i)$, estimated from simulated sky maps as described in Section 3.5.1. The solid curve is the PFD, $p(S_i | S_m, \sigma_m)$. All distributions have been normalized such that the integral under the curve is equal to 1. The vertical line indicates the local maximum of $p(S_i | S_m, \sigma_m)$, which gives the deboosted flux density of the source listed in column 4 of Tables 3.1 and 3.2.
Figure 3.7. Number of expected false detections in the AzTEC/COSMOS catalog above a given $S/N$ (left panel) and measured source flux density (right panel). The number of false detections determined here represents an upper limit to the real number of false detections that we expect (see Section 3.5.2). The error bars show $2\sigma$ Poisson errors.

An alternative definition for the expected number of false detections could be the number of “source” detections at points on the noiseless, beam-convolved sky with intrinsic flux below $S$, where $S$ could be the detection threshold of a follow-up observation, for instance with the SMA. But we refrain from such speculation here because the number of false detections would depend on the source population as well as the rather arbitrary $S$.

3.5.3 Completeness

The differential completeness as a function of input source flux is shown in Figure 3.8. Completeness is estimated by injecting sources, one at a time, into the (sparsely populated) real signal map at random positions and checking if they are retrieved by our standard source identification algorithm. Adding one source at a time to the real signal map provides a valid estimate of the completeness because: 1) it accounts for the effects of random and confusion noise present in the real map; 2)
it does not significantly alter the properties of the real map (only adding one source at a time); and 3) it does not depend on a model of the source population (as is necessary for fully simulated data-sets using noise maps). We inject a total of 1,000 sources per flux value, ranging from 0.5 – 12 mJy in steps of 0.5 mJy. A source is considered to be recovered if it is detected with $S/N \geq 3.5$ within 10′′ of the input source position. We disregard any samples where the input source is injected (or retrieved) within 10′′ of a real $\geq 3.5\sigma$ source candidate in the map to avoid confusion with bright sources. The AzTEC/COSMOS survey is 50% complete at 4 mJy, and 100% complete at 7 mJy.

**Figure 3.8.** Differential completeness versus intrinsic source flux density for the AzTEC/COSMOS survey. The errors represent the 95% confidence interval from the binomial distribution.
3.5.4 Positional Uncertainty

The simulations described in Section 3.5.3 offer a measure of the error on the position of sources identified in the AzTEC map due to the effects of both random and confusion noise. For the synthetic sources that are recovered, we calculate the distance between the input and output source positions and construct the probability, \( P(\theta; S/N) \), that an AzTEC source detected with a significance of \( S/N \) will be detected outside a radial distance \( \theta \) of its true position. This positional uncertainty measurement does not include the contribution from systematic pointing errors arising from uncertainties in the pointing model (Section 3.2.1), which are \( \lesssim 2'' \) (Section 3.6.2). A plot of the positional uncertainty distribution as a function of radial offset for three different \( S/N \) bins is shown in Figure 3.9. For all \( \geq 3.5\sigma \) AzTEC source candidates, the probability that an AzTEC source will be detected within 6'' of its true position is \( \geq 80\% \). For comparison, the analytic radial offset distribution derived in Ivison et al. (2007), which is given by

\[
P(\theta; S/N) \propto \int_{\theta}^{\infty} \theta' \cdot \exp \left( -\frac{\theta'^2}{2\sigma_p^2} \right) d\theta'
\]

(3.5)

where \( \sigma_p = (2\sqrt{\ln2})^{-1} \cdot \text{FWHM}/(S/N) \) and assuming a symmetric Gaussian beam with FWHM = 18'', are shown as dashed lines in Figure 3.9; these agree quite well with the fully simulated positional uncertainty distributions calculated here.

3.6 Comparison with Other Catalogs

A complete multi-wavelength analysis of the 15 brightest AzTEC sources in the COSMOS field is presented in Younger et al. (2007, 2009) and summarized in Section 3.9, and the multi-wavelength properties of the fainter source candidates will be presented in a future paper. In this Section, we discuss the confirmations of AzTEC sources with observations by Bolocam, identify the SMGs with potential radio and
Figure 3.9. The positional uncertainty distribution, $P(\theta; S/N)$, for three sample $S/N$ bins of the AzTEC/COSMOS source candidates. This shows the probability that an AzTEC source detected with a significance of $S/N$ will lie outside a radial distance $\theta$ from its true position. The blue, green, and red squares were determined from the simulations described in Section 3.5.4; the error bars show 1σ Poisson errors. The corresponding dashed curves of the same color show the analytic function from Ivison et al. (2007).
MIPS 24 \(\mu m\) counterparts, and study the faint mm emission from the rest of the radio/mid-IR population.

### 3.6.1 AzTEC Overlap with Bolocam Sources

The AzTEC/COSMOS field overlaps slightly with the larger, shallower Bolocam/COSMOS survey. Two of our high-significance source candidates lie within 4\(''\) of Bolocam-identified sources detected with \(S/N \geq 3.5\), confirming the reality of these sources (J. Aguirre, private communication). The third Bolocam source that lies within the AzTEC 75\% uniform coverage region is not detected in our survey.

Two additional Bolocam-detected sources lie within the 25\% uniform coverage region of the AzTEC map (the 2.5 mJy/beam contour shown in Figure 3.2). We tentatively confirm these two Bolocam sources at the \(\sim 3\sigma\) level. Though located 17 – 18\(''\) from the Bolocam centroid, these AzTEC source candidates are within the 95\% confidence radius of the positional error in the Bolocam/COSMOS survey (J. Aguirre, private communication). These four AzTEC sources which are coincident with Bolocam detections are identified in Tables 3.1 and 3.2.

### 3.6.2 The Corresponding Radio Population

The identification of radio counterparts has often been used to improve on the positional uncertainty of SMGs (e.g. Ivison et al., 2002, 2007; Chapman et al., 2003, 2005; Pope et al., 2005, 2006). For this comparison we use the 4.5\(\sigma\) catalog from the VLA/COSMOS survey (Schinnerer et al., 2007), which has a 1\(\sigma\) root-mean-square (rms) depth of 10.5 \(\mu Jy\). To identify potential radio counterparts to our mm-identified sources, we use a conservatively large search radius of 9\(''\) from the measured AzTEC source position. If we assume that the location of a candidate radio counterpart is the true location of a given AzTEC source, then the probability that we detect the AzTEC source at a distance greater than 9\(''\) from the radio source is given by the positional uncertainty distribution that was calculated in Section 3.5.4, \(P(> 9''; S/N)\), which is...
\[ p(\theta) = 1 - e^{-n\pi\theta^2} \] (3.6)

where \( n \) is the number density of radio sources (e.g., Scott & Tout, 1989). This p-statistic is equivalent to the probability that a radio source will lie within a distance \( \theta \) of an AzTEC source candidate by chance. Assuming uniform density (i.e. no clustering) of radio sources, \( n = 2350 \text{ deg}^{-2} \) in this field, and thus \( p(9''\) = 4.5\%. Hence we expect 4.5\% of radio sources identified within 9" of an AzTEC source candidate to be false associations.

For the list of \( \geq 3.5\sigma \) source candidates, 15 have a single radio counterpart within 9" of the AzTEC source position, and three have two radio sources within 9" of the AzTEC source position. AzTEC sources with at least one candidate radio counterpart are identified in Tables 3.1 and 3.2. From the p-statistic, we expect one of these 18 to be a false association. However, we may expect more false associations than this if radio sources cluster on scales smaller than 9", making the local p-statistic in the neighborhood of mm-sources higher. The fraction of AzTEC sources with potential radio counterparts (36\%) is consistent with that found in the SCUBA/SHADES survey (Ivison et al., 2007) of 30 – 50\%, assuming the same limiting flux (45 \( \mu \)Jy at 1.4 GHz), but is only marginally consistent (within 2\( \sigma \), Poisson errors) with that of the MAMBO/COSMOS survey (Bertoldi et al., 2007) of 67\%. Given the depth of the radio survey from Bertoldi et al. (2007, \( 7 – 8 \mu Jy \)), this may simply reflect the relative completeness in the different radio catalogs. Our radio fraction could also be
diluted by including low $S/N$ AzTEC sources, which have a higher number of false detections. The fraction of AzTEC $\geq 4\sigma$ sources (only two false detections expected) with candidate radio counterparts is $13/30$ (43%) and agrees with the Bertoldi et al. (2007) radio fraction within $1\sigma$.

We use the same radio catalog to explore the weaker, confused population of SMGs in the AzTEC map. Figure 3.10 (left panel) shows the results of averaging the AzTEC map flux in $2 \times 2$ arcmin$^2$ postage stamps extracted from regions centered at the 598 radio source positions that lie within the AzTEC map boundary. Since we compute a weighted average for each pixel, we extend this analysis to the noisier edges of the mm-map (10% coverage region, with an area of 0.28 deg$^2$). All radio sources that have candidate AzTEC counterparts detected with $|S/N| \geq 3.5$ have been excluded in order to restrict this analysis to radio sources with faint AzTEC emission, below the $S/N$ threshold used for discrete source identification. The $8.06\sigma$ stacked signal implies a mean 1.1 mm flux of $487 \pm 60 \mu$Jy for the radio sources in the catalog. No significant difference in the average 1.1 mm flux is detected when we stack separately on two groups of radio sources divided by their 1.4 GHz flux. For radio sources with flux density $> 66 \mu$Jy (293/598), the stacked 1.1 mm signal is $530 \pm 87 \mu$Jy, while the stacked 1.1 mm flux for radio sources $\leq 66 \mu$Jy (305/598) is $465 \pm 84 \mu$Jy. These values differ by only 13% and agree within the errors.

In the top right panel of Figure 3.10, we show a histogram of the 1.1 mm $S/N$ ratio at the location of all 598 radio sources. For comparison, we generate 100 fake catalogs, each with 598 positions chosen randomly across the AzTEC map, and construct the histogram of AzTEC $S/N$ ratio at these locations. Since these positions were chosen at random, we expect that the distribution of $S/N$ values should be nearly symmetric about zero. The bottom right panel of Figure 3.10 shows the difference between the histogram of the $S/N$ ratios at the radio source positions and that at the random positions. This clearly demonstrates that there is a significant contribution to the
Figure 3.10. Results from stacking the AzTEC/COSMOS map at the positions of radio sources. Left: Average AzTEC map flux in $2 \times 2$ arcmin$^2$ cutouts centered at the 598 radio source positions. We have excluded the positions of radio sources that are located within 9$''$ of AzTEC peaks with $|S/N| \geq 3.5$. Top Right: Histogram of the $S/N$ ratio of the 1.1 mm map at the radio source positions (red) versus that at positions chosen randomly in the map (black). Bottom Right: The difference between these two histograms.
stacked flux image from low $S/N$ mm-sources. Roughly 1/2 of the stacked signal arises from sources with $S/N < 1.8$ that fall below the detection threshold for source identification. This analysis demonstrates that the AzTEC map is sensitive to very faint mm emission down to flux levels on order of the 1$\sigma$ rms of the map.

The radio source stacking analysis can also be used to estimate the residual systematic and rms pointing errors in the AzTEC map due to errors in the astrometry. The stacked signal peaks at $(\Delta RA, \Delta Dec) = (0.4'', -2.1'')$, indicating a potential small systematic offset. Noise in the pointing solution leads to a broadening of the stacked signal, and so we use a measure of this broadening to determine the rms pointing uncertainty of our AzTEC observations. The model is as follows: assuming that the pointing errors are random and Gaussian distributed with mean zero and standard deviation $\sigma_p$, the stacked AzTEC flux should be equal to the convolution of a 2-dimensional Gaussian (with standard deviation $\sigma_p$) with the point source kernel. We calculate the cross-correlation of the stacked AzTEC flux at the radio source locations with this model, varying $\sigma_p$. We find that for all values of $\sigma_p$, the maximum value of the cross-correlation matrix is at an offset of zero in RA and $-2''$ in Dec, consistent with a small systematic pointing offset. Figure 3.11 shows the value of the maximum correlation as a function of pointing uncertainty, $\sigma_p$. The strongest correlation occurs for $\sigma_p = 0.89''$. However, the curve becomes very flat at $\sigma_p < 2''$ because the stacked image itself is limited to 2'' pixelization. Also, if radio sources in the COSMOS field cluster on scales $< 2''$, this would also broaden the width of the stacked signal, further complicating this estimate. Though we cannot accurately measure the value of $\sigma_p$ with this technique when $\sigma_p$ is small, we can state with confidence that $\sigma_p < 2''$, and we adopt this as a conservative estimate of the error in the astrometry in our map.
Figure 3.11. Cross-correlation between the stacked AzTEC/COSMOS signal at the radio source positions and a model for the broadening due to random pointing errors. The maximum correlation occurs at $< 2''$; this gives a conservative upper limit to the random pointing error in the AzTEC map. See Section 3.6.2 for details.
Table 3.3. Comparison of AzTEC/COSMOS source candidates with radio and MIPS 24 μm sources. \(p(9\arcsec)\) is the probability of a chance coincidence within the 9\arcsec search radius.

<table>
<thead>
<tr>
<th>AzTEC source candidates with ≥ 1 counterpart</th>
<th>AzTEC source candidates with 2 counterparts</th>
<th>Catalog Completeness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radio</td>
<td>18/50 (36%)</td>
<td>4.5% 4σ=45μJy</td>
</tr>
<tr>
<td>24 μm</td>
<td>32/49 (65%)</td>
<td>24.5% 5σ=60μJy</td>
</tr>
</tbody>
</table>

3.6.3 Coincident 24 μm Detections

A similar comparison can be made to sources detected at 24 μm by the *Spitzer* MIPS instrument in the S-COSMOS deep survey (Sanders et al., 2007). There are 2082 24 μm sources with \(S/N \geq 5\) \(\left(S_{24\text{μm}} \geq 60 \mu\text{Jy}\right)\) within the 75% uniform coverage region of the AzTEC/COSMOS map, and 49/50 AzTEC source candidates within the coverage of the MIPS 24 μm image. Of these, 30 AzTEC sources have a single 24 μm source found within 9\arcsec, while two AzTEC sources have two 24 μm sources within a 9\arcsec radius. AzTEC sources with one or more potential MIPS 24 μm counterparts are identified in Tables 3.1 and 3.2. The source density of 24 μm sources in this field is quite large \(14280 \text{ deg}^{-2}\) and the probability of chance coincidence within 9\arcsec is 24.5%, so we expect 12 false associations. As shown in Younger et al. (2007, 2009), it is not uncommon to find an unrelated 24 μm source within 9\arcsec of an SMG. We therefore do not use the 24 μm catalog as a signpost for mm wavelength emission. A summary of the number of AzTEC source candidates with potential radio and 24 μm counterparts is given in Table 3.3.

We perform the same stacking analysis as done for the radio catalog on the 24 μm catalog. The results are shown in Figure 3.12. Again, MIPS sources within 9\arcsec of an AzTEC pixel with \(|S/N| \geq 3.5\) have been excluded. This leaves 3129 MIPS sources within the extended AzTEC map. The stacked signal strength is 12.8σ, and the mean 1.1 mm flux of these sources is 324 ± 25 μJy. A histogram of the 1.1 mm
Results from stacking the AzTEC/COSMOS map at the position of MIPS 24 μm sources. Left: Average AzTEC map flux in 2 × 2 arcmin² cutouts centered at 3129 24 μm source positions. We have excluded the positions of 24 μm sources that are located within 9″ of AzTEC peaks with |S/N| ≥ 3.5. Top Right: Histogram of the S/N ratio of the 1.1 mm map at the 24 μm source positions (red) versus that at positions chosen randomly in the map (black). Bottom Right: The difference between these two histograms.

S/N ratio at the location of all 3129 MIPS 24 μm sources is shown in the right panel of Figure 3.12, demonstrating that the stacked signal is dominated by low (< 2σ) S/N mm-sources.

3.7 The Contribution of AzTEC Sources in COSMOS to the Cosmic Infrared Background

Using the deboosted 1.1 mm AzTEC flux densities derived from the PFDs, we sum the flux densities of the ≥ 3.5σ source candidates to determine the resolved fraction of the Cosmic Infrared Background (CIB) in this survey. An integrated flux of 1.3 Jy deg⁻² from those galaxies in the AzTEC catalog (Tables 3.1 and 3.2) is compared to 18 – 24 Jy deg⁻² from the CIB measured by COBE-FIRAS at 1.1 mm (Puget et al., 1996; Fixsen et al., 1998), demonstrating that we have resolved 5.3 –
7.1% of the CIB into bright mm-wavelength sources in the COSMOS field. This value is likely an overestimate of the real CIB resolved in this study because at least some of the source candidates are false detections (random noise peaks). Also, there appears to be an over-density of bright mm-sources in this field, in which case the local CIB would be larger than the average value over the full sky reported by Puget et al. (1996) and Fixsen et al. (1998).

Furthermore, we can estimate the fraction of the 1.1 mm CIB resolved by the entire radio population in the COSMOS field. Assuming that all of the 598 1.1 mm-faint radio sources (i.e. those undetected at $S/N \geq 3.5$ in the AzTEC/COSMOS map) distributed over an area of 0.28 deg$^2$ have a 1.1 mm flux density of $487 \pm 60 \mu$Jy as measured from the stacking analysis in Section 3.6.2, this radio population contributes an integrated flux of $1.0 \pm 0.1$ Jy deg$^{-2}$ to the CIB at 1.1 mm. This resolved fraction ($4.3 - 5.7\%$) is comparable to that measured from stacking the 850 $\mu$m flux at the position of 1.4 GHz radio sources in the SCUBA/GOODS-N field, where Wang et al. (2006) resolve $3.4 - 4.8\%$ of the CIB (excluding the contribution from $\geq 4\sigma$ sources) using a radio catalog with a similar limiting flux ($40 \mu$Jy) as the COSMOS radio catalog. Adding the contribution of $0.46$ Jy deg$^{-2}$ at 1.1 mm from the 18 bright ($S/N \geq 3.5$) AzTEC sources that have radio counterparts, we conclude that our AzTEC map has resolved a total 1.1 mm integrated flux of $1.46$ Jy deg$^{-2}$, or $7 \pm 1\%$ of the CIB, due to the full population of radio sources in COSMOS.

In a similar way, we estimate the contribution of MIPS 24 $\mu$m sources to the CIB at 1.1 mm from the stacking results presented in Section 3.6.3. The integrated flux at 1.1 mm from these mm-faint 24 $\mu$m sources is $4.4 \pm 0.3$ Jy deg$^{-2}$, or $18.3 - 24.4\%$ of the CIB. Similarly Wang et al. (2006) resolve $13.4 - 19.0\%$ of the CIB from their 850 $\mu$m stacking analysis of MIPS 24 $\mu$m sources in the SCUBA/GOODS-N map. Although their 24 $\mu$m catalog is slightly shallower than the COSMOS MIPS
24 $\mu$m source catalog (80 $\mu$Jy and 60 $\mu$Jy, respectively), these CIB fractions agree within the errors of the measurements.

### 3.8 Correlation between Millimeter-Selected Galaxies and Foreground Large-Scale Structure in COSMOS

We report an over-density of bright SMGs in the AzTEC/COSMOS survey and a spatial correlation between the SMGs and the optical/IR galaxy density at $z \lesssim 1.1$ in Austermann et al. (2009b). We summarize the analysis and major results from this study in this Section.

It is immediately clear that the AzTEC/COSMOS field is rich in bright mm-sources when compared to other 1.1 mm surveys of similar size and depth. The density of sources in this field with raw measured fluxes $\geq 6$ mJy is three times higher (14 sources in a 0.15 deg$^2$ field) than in the 1.1 mm Bolocam Lockman Hole survey of similar depth (three sources in a 0.09 deg$^2$ field, Laurent et al., 2005). To quantify the significance of this over-density, we compare the projected number density of SMGs in this field to that expected from an unbiased survey. The tightest constraint on the blank-field 1.1 mm number counts is currently provided by the 0.5 deg$^2$ AzTEC/SHADES survey (Austermann et al., 2009a). We use the semi-Bayesian method outlined in Coppin et al. (2005, 2006) to estimate the number counts from both surveys. We have further developed and extensively tested this method for use with AzTEC data as described in Austermann et al. (2009a,b). The cumulative number counts from the AzTEC/COSMOS survey are clearly in excess of those from AzTEC/SHADES (see Figure 4.7). To estimate the probability of this excess happening by chance, we compare the number of robust sources detected in the AzTEC/COSMOS survey to the average number recovered in 10,000 simulated maps, each populated with a random realization of the AzTEC/SHADES counts. We find that the number of robust sources ($S/N \gtrsim 4$) in the AzTEC/COSMOS map
is greater than that found in 99.7% of the simulated maps: a $3\sigma$ significance. The AzTEC/COSMOS source over-density is even more significant in the number of very bright sources, with 11 detected at $S/N \geq 5$. Ten thousand simulations of the blank-field model could produce no more than six such detections in a single map, inferring a $\gg 4\sigma$ significance in the number of bright mm-sources.

If taken alone, this over-density of SMGs in the AzTEC/COSMOS field would likely be explained away as cosmic variance in the SMG population as traced in a $0.15\text{ deg}^2$ field. However through several correlation tests presented in Austermann et al. (2009b) we show that this over-density is due in part to a correlation of AzTEC sources with the prominent large-scale structures traced by optical/IR galaxies at $z \lesssim 1.1$ identified in this portion of the COSMOS field. In the bottom left of Figure 3.13 we show the galaxy density map of optical/IR-selected galaxies from Scoville et al. (2007a). The cross and plus symbols mark the positions of AzTEC sources detected with $S/N \geq 4$ and $4 > S/N \geq 3.5$, respectively. Comparing the distribution of the galaxy densities at $z \lesssim 1.1$ projected within $30'$ of $S/N \geq 4$ AzTEC source positions to that found around random positions, a two-sided Kolmogorov-Smirnov (KS) test rejects the null hypothesis that the two distributions are drawn from the same parent distribution with $\geq 99.99\%$ significance. The mean number of nearby optical/IR galaxies at the AzTEC source positions is larger than that at random positions in the map at a significance of 99.99% according to the non-parametric Mann-Whitney (MW) $U$-test.

We next search in redshift-space for the structures that contribute the most to this correlation using photometric redshifts for the optical/IR sources (Ilbert et al., 2009), which have a mean accuracy of $\Delta z/(1 + z) = 0.01 - 0.02$. In the top right of Figure 3.13 we show a bar representation of the MW probabilities that the mean-integrated galaxy density around AzTEC sources is significantly larger than that around random positions in the map for various redshift slices. There is positive signal
(\gtrsim 2\sigma) arising at different redshift slices, most notably at \(z \sim 0.65\), which includes filamentary structure that leads to a massive cluster (\(\sim 10^5 \text{ M}_\odot\)) at \(z = 0.73\) (Guzzo et al., 2007). If we mask a region of radius 6' (\(\sim 2.4\) Mpc) centered on this structure, the MW significance decreases only slightly from 99.98% to 98.6%, demonstrating that this structure does not dominate the correlation. Masking similar structures in other redshift bins confirms that the AzTEC source positions are significantly correlated with less prominent large-scale structures across the entire map.

Parametric fits to the number counts suggest that the apparent over-density of SMGs in this field is more consistent with an average flux amplification of the population by \(\sim 30\%\) than a uniform physical over-density (e.g. cosmic variance) of sources. For the 15 AzTEC sources that have been followed up with SMA interferometry plus the additional six \(\geq 4\sigma\) sources with radio counterparts (for which secure optical/IR counterparts have been identified), photometric redshift estimates of these sources place the majority at \(z \gtrsim 3\); therefore, the AzTEC sources are most likely background sources to the \(z \lesssim 1.1\) galaxies shown in Figure 3.13. Given the over-density of foreground galaxies in this field we may expect an increased probability of lensing by individual galaxies (e.g. Dunlop et al., 2004). However, inspection of the optical/IR counterparts for the 21 securely-identified AzTEC/COSMOS sources shows no obvious signs of strong galaxy-galaxy lensing. Weak lensing by massive clusters at intermediate redshifts has long been used to detect and study SMGs and provides a natural explanation for the amplification in flux densities of background mm-sources. However, the AzTEC positions are not well-correlated with the weak-lensing mass map of COSMOS (Massey et al., 2007), which is particularly sensitive to the most massive structures like the \(z = 0.73\) cluster (consistent with the result that masking regions of known massive structures in the galaxy density map does not significantly reduce the correlation strength). This suggests that the AzTEC sources are primarily
Figure 3.13. COSMOS galaxy density map of optical/IR sources and its correlation with AzTEC source positions. **Bottom Left**: The mean-subtracted and smoothed surface density map of galaxies derived from the optical/IR catalog of COSMOS galaxies (Scoville et al., 2007a) in the 0.15 deg$^2$ region surveyed by AzTEC. The cross and plus symbols represent AzTEC sources detected at $S/N \geq 4$ and $4 > S/N \geq 3.5$, respectively. **Top Right**: Bar representation of the Mann-Whitney probability that the mean optical/IR galaxy density around AzTEC sources is significantly larger than the mean galaxy density around random positions. Horizontal dotted lines represent the 1$\sigma$, 2$\sigma$, and 3$\sigma$ significance levels. The blue dotted curve shows the relative number of optical/IR galaxies contained within each redshift slice ($N_{\text{gal}}(z)/N_{\text{total}} \times 10 + 0.6$) within the AzTEC covered region.
amplified by the more tenuous filamentary large-scale structures in this field rather than the compact massive clusters.

### 3.9 Interferometric Imaging of AzTEC/COSMOS Sources with the Submillimeter Array

We initially followed-up seven of the brightest SMGs in the AzTEC/COSMOS field with high-resolution (FWHM = 2") 890 µm interferometric imaging using the SMA; these results are presented in Younger et al. (2007) and are summarized here. We detected all of the AzTEC sources in this sample with S/N > 6, achieving typical rms noise levels of 1.0 – 1.5 mJy. While several interferometric observations at mm (Downes et al., 1999; Frayer et al., 2000; Dannerbauer et al., 2002, 2008; Downes & Solomon, 2003; Genzel et al., 2003; Neri et al., 2003; Sheth et al., 2004; Kneib et al., 2005; Greve et al., 2005; Tacconi et al., 2006, 2008; Frayer et al., 2008; Schinnerer et al., 2008; Daddi et al., 2009a,b) and submm (Iono et al., 2006; Younger et al., 2008a,b; Wang et al., 2007) wavelengths have been made for a large number of SMGs (∼ 30), this work represents the first time that a uniformly selected sample of SMGs from the same survey, including those without radio counterparts, has been carried out. The 0.2" positional accuracy afforded by these measurements allows us to identify secure radio, IR, and optical counterparts to these SMGs; multi-wavelength images for these seven SMGs are shown in Figure 3.14. Following the unprecedented success of these observations, we have extended this survey to eight additional SMGs in the AzTEC/COSMOS field (Figure 3.15; Younger et al., 2009), yielding an unbiased flux-limited sample of 15 bright SMGs with complete interferometric follow-up. The 890 µm flux densities of these sources are listed in column 5 of Table 3.1. Ten out of 15 of these SMGs were detected with high-significance (S/N ≥ 5) and are considered robust detections. Additionally, 3/15 SMGs detected with S/N < 5 are considered robust due to coincident detections at radio, IR, and/or optical wavelengths. For two
SMG candidates, AzTEC13 ($S/N \approx 5$) and AzTEC14 (resolved into two separate galaxies with $S/N \approx 5$ and 4), the 890 $\mu$m emission is not aligned with any counterparts at radio, IR, or optical wavelengths, and so these detections are considered tentative.

Ten of these 15 SMGs have either weak ($S_{20\text{cm}} < 60 \mu$Jy) or no radio counterparts, which we designate as radio-dim. We find that nearly all (13/15) of these sources have IRAC 3.6 and 4.5 $\mu$m counterparts (with IRAC catalog 5$\sigma$ depths of 0.9 and 1.7 $\mu$Jy, respectively). All five of the radio-bright SMGs have 24 $\mu$m counterparts, whereas only 2/10 radio-dim SMGs have bright 24 $\mu$m counterparts ($> 7\sigma \approx 100 \mu$Jy). There are often several 24 $\mu$m sources within the AzTEC beam that are not associated with the submm/mm emission. This is contrary to the prevailing wisdom in which radio-dim SMGs, like their radio-bright counterparts, are associated with redshifted strong polycyclic aromatic hydrocarbon (PAH) emission features in the 24 $\mu$m band. For 7/10 of the radio-dim sources there are proximate 24 $\mu$m sources that, if selected, would lead to misidentification of the multi-wavelength counterparts to the AzTEC source. Two of the radio-bright SMGs (AzTEC5 and AzTEC8) have two potential radio counterparts within the AzTEC beam; only the SMA observations can distinguish which is the source of mm emission.

These data also provide sufficient statistics for testing the radio-submm/mm association, which uses the local FIR to radio correlation (Condon, 1992) combined with statistical arguments to associate SMGs with nearby radio sources (e.g. Pope et al., 2006; Ivison et al., 2007). Of the nine SMGs in this sample with $\geq 3\sigma$ radio sources located within the AzTEC beam, we find only one instance in which none of the radio detections within the AzTEC beam is also detected in the high-resolution SMA maps – consistent with the expected number of false associations given the radio source density. This suggests that when submm/mm interferometry is not available, it is
Figure 3.14. Multi-wavelength images for the first seven AzTEC sources imaged with the Submillimeter Array (SMA) (Younger et al., 2007). Left to right: SMA 890 μm; VLA 20 cm; MIPS 24 μm; IRAC 3.6 μm; and HST/ACS i-band. Overlaid in red on the SMA image are 1.1 mm contours at 3σ, 4σ, ... from AzTEC. The red circles in the remaining postage stamps have a radius of 2″, corresponding to twice the FWHM of the SMA beam, and mark the SMA position. Each stamp image is 37″ × 27″, with the exception of the ACS stamps which are 15″ × 11″.
Figure 3.15. Multi-wavelength images for eight AzTEC sources imaged with the Submillimeter Array (SMA) (Younger et al., 2009). Left to right: SMA 890 µm; Subaru R-band; HST/ACS z-band; IRAC 3.6 µm; MIPS 24 µm; and VLA 20 cm. Overlaid in red on the SMA image are 1.1 mm contours at 3σ, 4σ, ... from AzTEC. The red circles in the remaining postage stamps indicate the SMA position and are 1″ in diameter – roughly 1/2 the SMA beam FWHM. The blues crosses indicate the locations of radio sources within the AzTEC beam. Each stamp is 25″ × 25″, with the exception of the ACS data, which shows a 5″ box indicated by a dotted rectangle.
reasonable to assume that a radio counterpart located within a suitable search radius of the AzTEC position is the source of mm emission.

Our interferometric imaging also constrains the submm morphology of these bright SMGs. All but one are best modeled as unresolved point sources, limiting their apparent angular size to $\lesssim 1.2''$. The one source that is resolved is best modeled as a double point source, and its visibility function is inconsistent with extended emission such as a Gaussian or disk morphology. Therefore all 15 bright SMGs in this sample are compact in the SMA imaging data, which at $z \sim 2 - 3$ corresponds to a physical scale of $\lesssim 9$ kpc. These sizes are consistent with those measured via higher resolution submm (Younger et al., 2008b) and radio (Chapman et al., 2004; Biggs & Ivison, 2008) data and rule out cool cirrus dust (e.g. Efstathiou & Rowan-Robinson, 2003) in the majority of bright SMGs.

The submm to radio flux ratio provides strong constraints on the redshifts of these sources (Carilli & Yun, 1999; Yun & Carilli, 2002). Limits on this flux ratio, combined with their non-detection at 24 $\mu$m and faintness in the IRAC bands, suggest that the 10 radio-dim SMGs in this sample are at $z \gtrsim 3$. Thus two-thirds of our flux-limited SMG sample are likely at redshifts higher than the median redshift of $z \sim 2.2$ determined from optical spectroscopic follow-up of radio-selected SMGs (Chapman et al., 2005). The presence of a significant population of these $L_{\text{FIR}} \sim 10^{13} L_\odot$ galaxies has important consequences for models of hierarchical galaxy formation, which are just now beginning to be able to account for such extreme systems at early epochs (e.g. Baugh et al., 2005).

3.10 Conclusions

We have imaged a 0.15 deg$^2$ region within the COSMOS field with AzTEC with uniform sensitivity of 1.3 mJy/beam at 1.1 mm. We have identified 50 source candidates in the AzTEC/COSMOS map with $S/N \geq 3.5$, 30 of which are detected
with \( S/N \geq 4.0 \) where the expected number of false detections is two. The sources are spread throughout the field, with only three detected within the region towards \( z = 0.73 \) cluster environment. Our catalog is 50% complete at an intrinsic flux density of 4 mJy, and is 100% complete at 7 mJy. The positional uncertainty of these AzTEC sources due to random and confusion noise is determined through simulations which show that sources with \( S/N \geq 3.5 \) have \( \geq 80\% \) probability of being detected within 6” of their true location. The availability of extensive high quality multi-wavelength data from the radio to the X-ray makes the follow-up analysis of the detected sources readily possible and will allow us to study the nature of these sources.

Comparing our \( \geq 3.5\sigma \) source candidate list with the COSMOS radio source catalog, we find that the fraction of AzTEC sources with potential radio counterparts is 36% and is consistent with that found in the SCUBA/SHADES survey (Ivison et al., 2007) at similar flux levels. From averaging the AzTEC map flux at the locations of the radio and MIPS 24 µm source positions, we statistically detect the faint mm emission (below our detection threshold) of radio and MIPS 24 µm sources and demonstrate that errors in the mean astrometry of our map arising from the pointing model are small (\(< 2''\)). Estimates of the resolved fraction of the CIB at 1.1 mm due to these radio and mid-IR galaxy populations is \( 7 \pm 1\% \) and \( 21 \pm 3\% \), respectively.

The AzTEC/COSMOS field samples a region of high galaxy over-density compared to the regions imaged with MAMBO and Bolocam, and our AzTEC/COSMOS map contains a large number of very bright mm-sources. The number counts from this survey represent a \( \sim 3\sigma \) increase over that expected from a blank-field, and we have measured a spatial correlation between the positions of the SMGs in this field with the galaxy density map from Scoville et al. (2007a). Fifteen of the \( \geq 5\sigma \) source candidates have been followed up and confirmed with SMA imaging (Younger et al., 2007, 2009), and their radio and mid-IR properties suggest that two-thirds of this
sample lie at $z \gtrsim 3$. Given that the galaxy density map traces optical/IR galaxies at $z \lesssim 1.1$, the apparent over-density of SMGs in this field and their correlation to the Scoville et al. (2007a) map is likely due to amplification of the background SMGs by the tenuous foreground structure.
CHAPTER 4

THE 1.1 MM AZTEC/ASTE GOODS-S MAP: SOURCE COUNTS FROM A CONFUSION-LIMITED SURVEY

4.1 Introduction

In this Chapter we present a 270 arcmin$^2$ survey of the Great Observatories Origins Deep Survey-South (GOODS-S) field taken with the 1.1 millimeter- (mm-) wavelength camera AzTEC operating on the 10-m Atacama Submillimeter Telescope Experiment (ASTE). This is the deepest survey at mm wavelengths ever carried out, achieving a root-mean-square (rms) noise level of $1\sigma \sim 0.6$ mJy. The GOODS-S field represents one of the most widely observed regions of sky, with deep multi-wavelength data from a number of ground-based and space-based facilities. This includes X-ray data from *Chandra* (Luo et al., 2008), optical to near-infrared (near-IR) photometry from the *Hubble Space Telescope* (*HST*; Giavalisco et al., 2004a), *Spitzer* IRAC (Chary et al., 2009) and MIPS (Dickinson et al., 2009) imaging in the mid-IR, submm imaging at 250 – 500 $\mu$m with the Balloon-borne Large Aperture Submillimeter Telescope (BLAST; Devlin et al., 2009), and 1.4 GHz interferometric imaging with the Very Large Array (VLA; Miller et al., 2008). Dedicated spectroscopic followup of optical sources in this field has also been underway (Vanzella et al., 2005, 2006, 2008; Popesso et al., 2009). This suite of multi-wavelength data is essential for the identification of counterparts to the submm/mm-selected galaxies (hereafter SMGs) in this field and for the characterization of their properties.

This Chapter is organized as follows: in Section 4.2 we describe the observations of the GOODS-S field carried out with AzTEC on ASTE. In Section 4.3 we summarize
the data reduction methods. We present the 1.1 mm map and source catalog in Section 4.4, and we describe simulations carried out to characterize the number of false detections, survey completeness, and degree of source blending in the map. We derive the 1.1 mm number counts from this survey in Section 4.5 and compare them with the number counts determined from Submillimeter Common User Bolometer Array (SCUBA) lensing cluster surveys at 850 µm and existing blank-field surveys at 1.1 mm wavelengths. We discuss the average 1.1 mm properties of BzK-selected galaxies in Section 4.6 and the contribution to the cosmic infrared background (CIB) at 1.1 mm from the radio and mid-IR galaxy populations in Section 4.7. We close with a summary of our results in Section 4.8. Two follow-up papers on the X-ray properties of the SMGs in this field (Johnson et al., 2009) and a comparison with the submm BLAST maps (Ferrusca et al., 2009) are underway.

4.2 Observations

We imaged a 28 × 22 arcmin² field centered at right ascension and declination (RA, Dec) = (03h32m30s, -27°48′20″) at 1.1 mm using AzTEC on the ASTE. The central 19 × 14 arcmin² region, where the coverage is very uniform, encompasses the entire GOODS-S region mapped by the Spitzer Space Telescope. The observations were carried out from July 15 to August 6 during the 2007 Chilean winter under generally excellent observing conditions, with τ220 = 0.05 on average, and τ220 < 0.06 70% of the time (zenith opacity at 220 GHz reported by the ASTE tau monitor). A total of 52 hours of observing time excluding pointing and calibration overheads was devoted to this survey. During the 2007 season, 107/144 of the AzTEC bolometers were operational with high sensitivity. The point spread function (PSF) of each detector was measured via beam-maps on Uranus, Neptune, and 3c279 as described in Section 2.2.2 and has a full width at half maximum (FWHM) of 30″ ± 1″ and
31" ± 2" in azimuth and elevation, respectively. The full array subtends a roughly circular field-of-view with a diameter of 8'.

4.2.1 Scan Strategy

We used a continuous scanning strategy which traces a modified Lissajous pattern on the sky:

\[
\begin{align*}
\Delta RA &= 5.5' \cdot \sin(a \cdot t + 0.25) + 2.0' \cdot \sin(a \cdot t/30) \\
\Delta Dec &= 7.5' \cdot \sin(b \cdot t) + 2.0' \cdot \sin(b \cdot t/30),
\end{align*}
\]

where \( a/b = 8/9 \) and \( \Delta RA \) and \( \Delta Dec \) are physical coordinates relative to the field center. The actual values of \( a \) and \( b \) were scaled to limit the peak scanning velocity to 300″/s, and a rotational angle 20.0° West of North was used in order to align our map with that of the Spitzer IRAC/MIPS coverage of GOODS-S. A single observation took 42 minutes to complete, and we obtained a total of 74 observations of the GOODS-S field.

The benefit of Lissajous-scanning, in addition to attaining excellent cross-linking and uniform coverage in the map, is that we avoid large telescope accelerations that can induce systematics in the detector signals as well as compromise the pointing accuracy of the telescope. Such effects are often seen in images taken in raster-scan mode, where \( 1/3 - 1/2 \) of the data taken during times when the telescope reverses direction must be discarded (e.g. Chapter 3; Scott et al., 2008; Perera et al., 2008). Lissajous-scanning, on the other hand, results in nearly 100% observing efficiency.

4.2.2 Pointing Corrections

We make small corrections to the telescope pointing model by routinely observing the bright point source J0455-462 (\( S_{1.1\text{mm}} \approx 1.4 \text{ Jy, variable} \)) every two hours before and after each GOODS-S observation. We measure pointing offsets by fitting the 4 ×
4 arcmin$^2$ maps of J0455-462 to 2-dimensional Gaussians, and we linearly interpolate these offset corrections (temporally) and apply them to the GOODS-S data. The random pointing error in the final GOODS-S map is $\lesssim 1''$ (see Section 4.4.2).

### 4.2.3 Flux Calibration

The flux conversion factor (FCF) used to convert the raw detector signals to flux density units is determined by beam-map observations on Uranus, Neptune, and 3c279, taken 1 − 2 times per night as described in Section 2.3. The flux densities of Uranus and Neptune at 1.1 mm were calculated from their frequency-dependent brightness temperatures reported in Griffin & Orton (1993) and ranged from 43−52 Jy and 18 − 20 Jy, respectively, during the AzTEC/ASTE 2007 observing season. The flux density of 3c279, which is highly variable, ranged from 7.0 − 9.4 Jy at 1.1 mm during this time. We remove the responsivity factor from the detector signals and correct for extinction by modeling both as a linear function of the demodulated dc-level (see Section 2.3.2).

The measured FCF varied significantly from night to night, resulting in a 1σ scatter of 17% over the entire observing run. We have identified the source of this scatter as the changing focal point of the telescope with environment temperature: the FCF decreases as the measured FWHM of the beam increases (Section 2.3.3.2). Since real-time corrections were not possible, we use the same-night measurement of the FCF to calibrate each observation. To estimate the total calibration uncertainty, we determine the standard deviation in the measured flux densities from the 68 pointing observations of J0455-462, which is 15%. Since this source is known to be variable, this gives a conservative upper limit to our calibration uncertainty. Combining this in quadrature with the 5% absolute uncertainty on the flux densities of Uranus and Neptune (Griffin & Orton, 1993) gives a total calibration error of 16%.
4.3 Data Reduction

We reduce the 1.1 mm data in a manner that is nearly identical to that described in detail in Section 3.3. We summarize the steps here and note the differences. The raw “time-stream” data, which consist of all bolometer signals and pointing data stored as a function of time, is first scanned for “spikes” (defined as any $> 7\sigma$ jump between sequential detector samples) that are caused by instrumental glitches or cosmic ray strikes. These data and nearby samples, which amount to $< 0.1\%$ of the total time-stream data, are flagged and discarded from the data-set. We group the remaining samples into 10-sec intervals, and then “clean” each 10-sec group using a principal component analysis (PCA) algorithm to identify and remove the common-mode atmospheric signal (Section 3.3.2; Laurent et al., 2005). For AzTEC maps taken in raster-scan mode (e.g. Chapter 3; Perera et al., 2008) data samples from the same individual scan (a single pass of the telescope across the sky) were grouped together for PCA cleaning. Since there is no such natural division for continuous Lissajous-scan maps, we chose a 10-sec interval grouping. Perera et al. (2008) showed via a statistical correlation analysis that this PCA cleaning technique using time intervals ranging from $5 - 15$ sec provides a good balance between using a sufficient number of samples to determine the bolometer-bolometer correlations and being on a short enough time scale so that the slower electronics related low-frequency drifts can be effectively removed. We have verified that cleaning on $5 - 20$ sec intervals gives consistent results for AzTEC/GOODS-S.

After cleaning the time-stream data, the bolometer signals are calibrated and binned into $3'' \times 3''$ pixels to make a map for each separate observation. These 74 maps are then co-added and optimally filtered for point source detection. In addition to this filtered map, we track the effects of PCA cleaning and filtering on a model point source (referred to hereafter as the point source kernel). The smoothing slightly broadens the FWHM of the beam: fitting a 2-dimensional Gaussian to the point

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source kernel results in a FWHM of 34.6″ and 34.3″ in RA and Dec, respectively. We also generate 100 noise maps, each a realization of the signal-free noise in the GOODS-S map, by “jackknifing” the time-stream signals in the same manner described in Section 3.3.4. The point source kernel and noise realizations are used later in the analysis for simulation purposes and number counts determination.

4.4 1.1 mm Map and Source Catalog

4.4.1 AzTEC 1.1 mm Map

The 1.1 mm map of GOODS-S taken with AzTEC on ASTE is shown in Figure 4.1. The map has been trimmed to show only the “50% uniform coverage region”, defined as the region where the coverage is greater than or equal to 50% of the maximum coverage in the map. The total area of this uniform coverage region is 270 arcmin², and the 1σ rms noise in this region ranges from 0.48 – 0.73 mJy/beam, making this the deepest contiguous region ever mapped at 1.1 mm. The scanning strategy that we used to map this field results in two separate patches where the coverage is deepest (0.48 mJy/beam), whereas the center of the map is slightly more shallow (0.56 mJy/beam, see contours on Figure 4.1). We restrict all analysis in this paper to this 270 arcmin² uniform coverage region. The noise in the map, determined from the jackknifed noise realizations, is extremely Gaussian over the entire field.

The AzTEC/GOODS-S survey is one of the deepest blank-field surveys at 1.1 mm ever achieved and is confusion-limited. From the blank-field 1.1 mm source counts from the AzTEC/SHADES survey (Austermann et al., 2009a) and the 30″ FWHM ASTE beam, the confusion-limit (one source per 40 beams) for AzTEC on ASTE is $1\sigma = 0.45$ mJy, near the rms noise level of the GOODS-S map. This has important implications for the interpretation of the data, and so we take considerable care to understand the effects of confusion noise on our methods throughout the following analyzes.
Figure 4.1. The AzTEC 1.1 mm map of the GOODS-S field. The map has been trimmed to show only the 270 arcmin$^2$ 50% uniform coverage region, to which source extraction and other analysis of this field is restricted. The dashed contours (innermost to outermost) indicate noise rms levels of 0.51, 0.57, and 0.78 mJy/beam. The circles (diameter = 2 × FWHM of AzTEC on ASTE = 60") indicate the locations of $\geq 3.5\sigma$ source candidates, labeled in order of decreasing $S/N$ of the detections.
4.4.2 Astrometry

To check for a systematic offset in the pointing, which could arise from mechanical issues or environmental effects on the telescope during observations, we stack the 1.1 mm GOODS-S map at the positions of radio sources in this field, whose positions are known to within 1″. From the VLA 1.4 GHz survey of the Extended Chandra Deep Field-South (ECDF-S; Miller et al., 2008), which reaches an rms noise level of 4.5 – 8.0 μJy, we extract a ≥ 4σ radio source catalog and stack the AzTEC map at the positions of the 219 radio sources that lie within the uniform coverage region; this results in an 8σ detection of the peak offset by −6.3″ ± 2.1″ in RA and −3.9″ ± 2.1″ in Dec. We have verified this result by stacking at the locations of 1185 MIPS 24 μm sources detected with signal to noise $S/N \geq 10$ in the Spitzer GOODS-S survey (Dickinson et al., 2009), which gives an 11σ peak detection offset by −6.3″ ± 1.6″ in RA and −0.7″ ± 1.6″ in Dec, consistent with the radio stacking results. We thus apply an astrometric correction of ($\Delta$RA, $\Delta$Dec) = (6.3″, 0.7″) to the AzTEC map and 1.1 mm source positions (we favor the offsets measured from the 24 μm stacking due to the higher $S/N$).

This systematic offset represents the average pointing offset between J0455-462 and the GOODS-S field over 74 observations. The scatter in this offset will manifest itself as random pointing error in the co-added map. We can estimate this random error from the broadening of the stacked signal with respect to the point source kernel. We adopt a simple model which consists of the convolution of the ideal point source kernel with a 2-dimensional Gaussian with standard deviation ($\sigma_{\text{RA}}$, $\sigma_{\text{Dec}}$), where $\sigma_{\text{RA}}$ and $\sigma_{\text{Dec}}$ are the 1σ random pointing errors in RA and Dec (see Section 3.6.2 for a full description of this measurement). The stacked 1.1 mm signal for both the radio and MIPS 24 μm populations is significantly broader than the point source kernel, implying random pointing errors of 1σ ≈ 6.8″ and 15″, respectively. However, we do not expect our random pointing errors to be so large, and this broadening is likely
caused by other effects such as confused/blended sources in the 1.1 mm image or clustering of the radio and 24 µm sources. As an alternate estimate of the random pointing error in the AzTEC map, we measure $\sigma_{\text{RA}}$ and $\sigma_{\text{Dec}}$ from the brightest AzTEC source in this field, AzTEC/GS1. The high $S/N$ of this source (11.6$\sigma$, see Table 4.1) allows a clean measurement and provides a stronger constraint on the random pointing error, since the signal from this single source can only be broadened with respect to the point source kernel due to the scatter in the pointing model. The maximum likelihood estimate for the random pointing error from AzTEC/GS1 is $(\sigma_{\text{RA}}, \sigma_{\text{Dec}}) = (0.5'', 0.1'')$; however, the distribution of $(\sigma_{\text{RA}}, \sigma_{\text{Dec}})$ is very flat out to 1'', then falls off steadily. From this we conclude that the random pointing errors in the AzTEC/GOODS-S map are $\lesssim 1''$.

### 4.4.3 Source Catalog

We identify point sources in the 1.1 mm $S/N$ map by searching for local maxima within 15'' of pixels with $S/N \geq 3.5$ (see Section 3.4 for a more detailed description). The 40 source candidates that meet this criterion are listed in Tables 4.1 and 4.2 in order of decreasing $S/N$ of the detection. These Tables includes both the 1.1 mm flux densities and 1$\sigma$ errors measured from the map, as well as the bias-corrected flux densities estimated using a semi-Bayesian technique (Section 4.5.2; Coppin et al., 2005, 2006; Austermann et al., 2009a,b). This flux-bias correction accounts for the fact that measured flux densities of mm-selected galaxies, which are generally detected at low $S/N$, are preferentially “boosted” due to the steep luminosity distribution of the population (e.g. Hogg & Turner, 1998).

Several of the source candidates appear extended in the 1.1 mm map, most notably, AzTEC/GS2 (see Figure 4.1). To separate the components of AzTEC/GS2, we fit the 1.1 mm map in the neighborhood of this source to a 2-component model, where each component is a scaled version of the point source kernel. The best-fit positions
and flux densities are listed in Table 4.1. Given the comparatively low \( S/N \) of the other AzTEC sources which appear extended, we are unable to separate them into multiple components.

### 4.4.4 False Detections

Due to the low significance of the detections, we expect some fraction of the AzTEC sources in GOODS-S to be spurious, i.e. noise peaks in the 1.1 mm map which are not associated with astronomical sources. The number of false positives is a function of \( S/N \), where sources found with higher \( S/N \) are less likely to be spurious. We estimate the number of false detections by identifying the number of “sources” extracted from the 100 pure noise realizations. The number of false detections expected as a function of limiting \( S/N \) ratio is shown in Figure 4.2 (solid curve, diamonds). At \( \geq 3.5\sigma \), we expect \( \sim 2\%/40 \) sources in our catalog (5\%) to be spurious. Above \( \geq 4.25\sigma \), none of the AzTEC sources are expected to be false positives.

This estimate however provides only an upper limit to the number of spurious detections. In the real map, the negative bias in the pixel flux distribution from the addition of sources decreases the number of high-significance positive noise peaks in the map. This effect was first demonstrated for the AzTEC/GOODS-N survey (Perera et al., 2008) and is even more pronounced for our confusion-limited GOODS-S map. To demonstrate this effect, we generate 600 sky realizations of the GOODS-S field using the noise maps and simulated point sources, each modeled as the point source kernel scaled by the source flux density. These simulated galaxies are injected at random positions in the noise maps and are drawn from a population described by the best-fit Schechter function to the AzTEC/GOODS-S number counts (Section 4.5). These maps, referred to hereafter as “fully simulated maps”, provide a realistic model of the mm-galaxy population in the GOODS-S field as observed by AzTEC by
<table>
<thead>
<tr>
<th>AzTEC ID</th>
<th>Source Name</th>
<th>$S/N$</th>
<th>$S_{1.1\text{mm}}$ (measured)</th>
<th>$S_{1.1\text{mm}}$ (deboosted)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AzTEC/GS1</td>
<td>AzTEC.J033211.46-275216.0</td>
<td>11.6</td>
<td>6.6 ± 0.6</td>
<td>6.3 ± 0.5</td>
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<tr>
<td>AzTEC/GS2</td>
<td>AzTEC.J033218.48-275221.8</td>
<td>11.4</td>
<td>6.0 ± 0.5</td>
<td>5.7 ± 0.6</td>
</tr>
<tr>
<td>GS2.1</td>
<td>AzTEC.J033218.99-275213.8</td>
<td>12.6</td>
<td>6.6 ± 0.5</td>
<td>6.3 ± 0.5</td>
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<tr>
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<td>AzTEC.J033216.70-275244.0</td>
<td>7.6</td>
<td>4.0 ± 0.5</td>
<td>3.7 ± 0.5</td>
</tr>
<tr>
<td>AzTEC/GS3</td>
<td>AzTEC.J033247.86-275419.3</td>
<td>9.4</td>
<td>4.8 ± 0.5</td>
<td>4.5 ± 0.5</td>
</tr>
<tr>
<td>AzTEC/GS4</td>
<td>AzTEC.J033248.75-274249.5</td>
<td>8.6</td>
<td>5.0 ± 0.6</td>
<td>4.6 ± 0.6</td>
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<tr>
<td>AzTEC/GS5</td>
<td>AzTEC.J033151.81-274433.9</td>
<td>7.8</td>
<td>4.8 ± 0.6</td>
<td>4.1 ± 0.6</td>
</tr>
<tr>
<td>AzTEC/GS6</td>
<td>AzTEC.J033225.73-275219.4</td>
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<td>3.4 ± 0.5</td>
<td>3.1 ± 0.5</td>
</tr>
<tr>
<td>AzTEC/GS7</td>
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<td>6.7</td>
<td>3.9 ± 0.6</td>
<td>3.5 ± 0.6</td>
</tr>
<tr>
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<td>3.1 ± 0.5</td>
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<tr>
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<tr>
<td>AzTEC/GS10</td>
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<td>3.5 ± 0.6</td>
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<tr>
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<td>AzTEC.J033215.79-275036.8</td>
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<td>3.1 ± 0.6</td>
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<tr>
<td>AzTEC/GS12</td>
<td>AzTEC.J033229.13-275613.8</td>
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<td>3.3 ± 0.5</td>
<td>2.9 ± 0.5</td>
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<tr>
<td>AzTEC/GS13</td>
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<td>3.1 ± 0.5</td>
<td>2.8 ± 0.5</td>
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<td>3.0 ± 0.5</td>
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<tr>
<td>AzTEC/GS15</td>
<td>AzTEC.J033150.91-274600.4</td>
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<td>4.0 ± 0.7</td>
<td>3.5 ± 0.7</td>
</tr>
<tr>
<td>AzTEC/GS16</td>
<td>AzTEC.J033237.67-274401.8</td>
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<td>2.5 ± 0.5</td>
</tr>
<tr>
<td>AzTEC/GS17</td>
<td>AzTEC.J033222.31-274816.4</td>
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<td>3.1 ± 0.6</td>
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<td>AzTEC/GS18</td>
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<tr>
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<td>2.4 ± 0.5</td>
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<tr>
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<tr>
<td>AzTEC/GS22</td>
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<td>2.0 ± 0.5</td>
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<tr>
<td>AzTEC/GS23</td>
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<td>2.5 ± 0.5</td>
<td>2.1 ± 0.5</td>
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<tr>
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<td>2.1 ± 0.5</td>
</tr>
<tr>
<td>AzTEC/GS25</td>
<td>AzTEC.J033246.96-275122.4</td>
<td>4.4</td>
<td>2.2 ± 0.5</td>
<td>1.8 ± 0.5</td>
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<td>AzTEC/GS26</td>
<td>AzTEC.J033215.79-274336.6</td>
<td>4.4</td>
<td>2.1 ± 0.5</td>
<td>1.8 ± 0.5</td>
</tr>
<tr>
<td>AzTEC/GS27</td>
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<td>2.3 ± 0.5</td>
<td>1.8 ± 0.5</td>
</tr>
<tr>
<td>AzTEC/GS28</td>
<td>AzTEC.J033242.71-275206.8</td>
<td>4.3</td>
<td>2.1 ± 0.5</td>
<td>1.7 ± 0.5</td>
</tr>
</tbody>
</table>
Table 4.2. AzTEC/GOODS-S source candidates detected with $3.5 \leq S/N < 4.25$. Only two of these source candidates are expected to be false positives. The columns are the same as those in Table 4.1.

<table>
<thead>
<tr>
<th>AzTEC ID</th>
<th>Source Name</th>
<th>$S/N$</th>
<th>$S_{1.1\text{mm}}$ (measured) (mJy)</th>
<th>$S_{1.1\text{mm}}$ (deboosted) (mJy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AzTEC/GS29</td>
<td>AzTEC_J033158.77-274500.9</td>
<td>4.1</td>
<td>$2.2 \pm 0.5$</td>
<td>$1.8^{+0.5}_{-0.6}$</td>
</tr>
<tr>
<td>AzTEC/GS30</td>
<td>AzTEC_J033220.94-274240.8</td>
<td>4.1</td>
<td>$2.0 \pm 0.5$</td>
<td>$1.7^{+0.5}_{-0.6}$</td>
</tr>
<tr>
<td>AzTEC/GS31</td>
<td>AzTEC_J033243.06-273925.6</td>
<td>4.1</td>
<td>$2.5 \pm 0.6$</td>
<td>$2.0^{+0.6}_{-0.7}$</td>
</tr>
<tr>
<td>AzTEC/GS32</td>
<td>AzTEC_J033309.35-275128.4</td>
<td>4.1</td>
<td>$2.8 \pm 0.7$</td>
<td>$2.1^{+0.7}_{-0.8}$</td>
</tr>
<tr>
<td>AzTEC/GS33</td>
<td>AzTEC_J033249.03-275315.8</td>
<td>4.1</td>
<td>$2.0 \pm 0.5$</td>
<td>$1.6^{+0.5}_{-0.6}$</td>
</tr>
<tr>
<td>AzTEC/GS34</td>
<td>AzTEC_J033229.77-274313.1</td>
<td>4.0</td>
<td>$2.0 \pm 0.5$</td>
<td>$1.6^{+0.5}_{-0.6}$</td>
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<tr>
<td>AzTEC/GS35</td>
<td>AzTEC_J033226.90-274052.1</td>
<td>4.0</td>
<td>$2.0 \pm 0.5$</td>
<td>$1.6^{+0.5}_{-0.6}$</td>
</tr>
<tr>
<td>AzTEC/GS36</td>
<td>AzTEC_J033213.94-275519.7</td>
<td>3.7</td>
<td>$2.1 \pm 0.6$</td>
<td>$1.5^{+0.6}_{-0.7}$</td>
</tr>
<tr>
<td>AzTEC/GS37</td>
<td>AzTEC_J033256.48-274610.3</td>
<td>3.7</td>
<td>$2.5 \pm 0.7$</td>
<td>$1.8^{+0.7}_{-0.8}$</td>
</tr>
<tr>
<td>AzTEC/GS38</td>
<td>AzTEC_J033209.26-274245.5</td>
<td>3.6</td>
<td>$1.8 \pm 0.5$</td>
<td>$1.4^{+0.5}_{-0.6}$</td>
</tr>
<tr>
<td>AzTEC/GS39</td>
<td>AzTEC_J033154.34-274536.3</td>
<td>3.5</td>
<td>$2.1 \pm 0.6$</td>
<td>$1.5^{+0.6}_{-0.7}$</td>
</tr>
<tr>
<td>AzTEC/GS40</td>
<td>AzTEC_J033200.38-274634.6</td>
<td>3.5</td>
<td>$1.9 \pm 0.6$</td>
<td>$1.4^{+0.6}_{-0.7}$</td>
</tr>
</tbody>
</table>

properly including the effects from our data reduction methods. We use these fully simulated maps throughout this Chapter to investigate various properties of our map.

We run the source-finding algorithm to detect sources in these fully simulated maps. For each detected source, we search within a 17" radius to identify the corresponding input source. Detected sources which cannot be traced back to an input source with intrinsic flux density $\geq 0.1$ mJy are deemed false positives. The number of false positives estimated from these fully simulated maps as a function of limiting $S/N$ is shown in Figure 4.2 (dashed curve, squares). From this estimate we expect at most one of the 40 $\geq 3.5\sigma$ sources in our catalog to be spurious. At $\geq 3.0\sigma$, the number of false positives estimated from these fully simulated maps is significantly lower than that estimated from pure noise realizations ($\approx 1$ versus $\approx 7$), suggesting that we can comfortably extend our source catalog to lower $S/N$ detections. However, these simulations do not include the effects of source clustering. If the mm-galaxy population is strongly clustered on small angular scales, the strength of the negative bias
Figure 4.2. The expected number of false detections in the AzTEC/GOODS-S map as a function of limiting $S/N$. The solid curve and diamonds show the number of false detections estimated from the number of peaks detected in pure noise realizations with significance $\geq S/N$, and is a conservative overestimate. The dashed curve and squares indicate the expected number of false positives determined from simulated maps.

in the pixel flux distribution would vary from region to region due to the variance in the source density, and thus the number of positive noise peaks (i.e. false positives) would be lower (higher) in the more (less) densely populated regions of the map. Since the clustering properties of the mm-galaxy population (including intrinsically faint sources) are not well known, we prefer to quote the values determined from the pure noise realizations as a conservative estimate of the number of false detections expected in our catalog.
4.4.5 Completeness

The detection rate for a given source flux density is affected by both Gaussian random noise in the map and confusion noise from the underlying bed of faint sources. To account for both effects, we estimate the survey completeness by measuring the recovery rate of point sources with known flux densities inserted into the real signal map, as described in Section 3.5.3. For flux densities ranging from 0.1 – 8.0 mJy, we input 2000 sources per flux density one at a time into the GOODS-S map, each time randomly selecting the source position. Using the standard source-finding algorithm, an input source is considered recovered if it is detected in the map within 17″ of its input position with a significance of \( \geq 3.5\sigma \). We exclude samples where the simulated source was input or extracted less than 17″ from a real \( \geq 3.5\sigma \) source. The survey completeness is shown in Figure 4.3 (red data-points with binomial error bars). The survey is 50% complete at 2.1 mJy, and 95% complete at 3.5 mJy.

The sea of faint sources below the detection threshold adds confusion noise to the AzTEC/GOODS-S map. This additional noise reduces the map’s sensitivity to individual sources and its survey completeness over a range of flux densities. An accurate estimate of the completeness is essential for correcting the observed number counts for this field. In the standard Bayesian method for extracting number counts from AzTEC maps (Austermann et al., 2009a,b), survey completeness is estimated by injecting sources of known flux density one at a time into noise realizations and determining their recovery rate. While this method does not take confusion noise into account, this estimate was found to be consistent with that measured from the real signal map using the method described in the previous paragraph for several AzTEC surveys on the James Clerk Maxwell Telescope (JCMT) with 1σ depths of \( \approx 1.0 \) mJy (e.g. Perera et al., 2008; Austermann et al., 2009a,b), demonstrating that confusion noise was not significant for these surveys. In contrast, we find that the completeness
Figure 4.3. The survey completeness for $S/N \geq 3.5$ AzTEC sources in GOODS-S. The red data-points and 95% confidence binomial error bars show the completeness estimated by inserting sources of known flux density one at a time into the real signal map. The solid curve shows the completeness estimated by fully simulated maps. The dashed curve shows the completeness estimated by inserting sources of known flux density one at a time into pure noise realizations and does not account for the effects of confusion noise.
estimated from noise-only maps significantly over-predicts the survey completeness for our deeper, confusion-limited GOODS-S map (Figure 4.3, dashed curve).

To verify that this difference arises from confusion noise, we next estimate the survey completeness from 10,000 fully simulated maps generated as described in Section 4.4.4. For each $\geq 3.5\sigma$ source detected in these simulated maps, we identify the brightest input source within 17$''$ of the output source position. We bin all detected sources by their input flux densities, and the completeness is calculated by the ratio of the number of recovered sources to the total number of input sources per flux bin. The completeness estimated from these fully simulated maps is shown as the solid curve in Figure 4.3. This estimate agrees quite well with that from the single-input source simulations using the real GOODS-S map. The discrepancy between the two methods at $S_{1.1\text{mm}} \lesssim 1.5$ mJy likely arises from small imperfections in the assumptions we use to identify input-output pairs. For example, the single-input source simulations may slightly overestimate the completeness at low flux densities due to cases when the input source is inserted close to (but $> 17''$) a bright mm-galaxy in the real map. On the other hand, the completeness from the fully simulated maps may be underestimated at $S_{1.1\text{mm}} \lesssim 1.5$ mJy in cases where input sources with these lower flux densities are rejected in favor of a nearby, brighter input source. Still, despite the very different methods used for these two different completeness estimates, they differ by $\leq 4\%$ at all flux densities.

### 4.4.6 Positional Uncertainty

The large beam combined with the low $S/N$ of the detections results in a large positional error on the locations of submm/mm-detected sources due to the effects of random and confusion noise in the map. We use the simulations described in 4.4.5, where a single source of known flux density is inserted into the GOODS-S map one at a time, to determine the distribution of input to output source distances
Figure 4.4. The positional uncertainty distribution for AzTEC/GOODS-S source candidates. The data-points and error bars show the probability $P(\theta; S/N)$ that an AzTEC source detected with a given $S/N$ value will be found outside a radial distance $\theta$ from its true location as determined from simulations. The curves show the analytical expression derived in Ivison et al. (2007): solid – $3.5 < S/N < 3.75$; dashed – $4.5 < S/N < 4.75$; and dotted – $5.5 < S/N < 5.75$. As a function of detected $S/N$. The probability $P(\theta; S/N)$ that a source will be detected outside of a radial distance $\theta$ of its true position is shown in Figure 4.4 for three sample $S/N$ bins. For comparison, the analytical solutions determined from Ivison et al. (2007, Equation 3.5) are shown as the solid ($3.5 < S/N < 3.75$), dashed ($4.5 < S/N < 4.75$), and dotted ($5.5 < S/N < 5.75$) curves, assuming that the FWHM of the AzTEC beam is $34''$ (i.e. the width of best-fit Gaussian to the filtered point source kernel). The analytical and empirical distributions agree quite well.
4.4.7 Source Blending

Given the depth and low angular resolution of the AzTEC/GOODS-S survey, some fraction of the $\geq 3.5\sigma$ sources in the map are expected to be the combined signal from two (or more) individual galaxies blended together. Indeed, many of the AzTEC sources in this field appear somewhat extended. To estimate the fraction of the sources in Tables 4.1 and 4.2 that are actually the blend of $\geq 2$ individual galaxies, we take the $\geq 3.5\sigma$ sources detected from the 600 fully simulated maps described in Section 4.4.4 and trace each one back to all input sources located within 17″ of the output source position. The fraction of detected sources that cannot be traced back to any input source is 0.8%; these represent the ”false positives” estimated from the fully simulated maps as described in Section 4.4.4. Sources that map back to only one input source are considered ”single sources”, while those that can be traced back to two or more input sources are considered ”blended sources”.

With this simple definition, the fraction of blended sources is very high (67%) given the high source density of faint SMGs. However, a very faint source nearby a relatively bright source (for example, a 0.2 mJy source located 10″ from a 3.0 mJy source) contributes a negligible amount to the summed signal. We want to avoid counting cases like these – where the brighter of the two sources completely dominates the total signal – as a blended source. As a more practical definition, we only consider a pair of nearby sources to be a blend if the contribution from each source to the summed signal is comparable. Using the input source flux densities and relative separations for all simulated sources within 17″ of an output source, we model the beam-smoothed noiseless signal from the sum of these point sources and measure the peak flux density. If the fractional contribution to the summed flux density for an individual input source at the location of the peak is $\geq 30\%$, the source is considered to contribute significantly to the detection. With this definition, 18% ($\approx 7/40$) of the AzTEC sources listed in Tables 4.1 and 4.2 are expected to be $\geq 2$ individual...
galaxies blended by the large beam. This fraction reduces to 7% if we require that an individual source contributes 40% to the summed noiseless flux density. These results represent lower limits to the fraction of blended sources, since this fraction would be even higher if the SMG population is significantly clustered.

4.5 Number Counts

4.5.1 Fluctuation Analysis

Due to the incredible depth reached by this survey, the mm emission from faint SMGs has a striking effect on the flux density distribution in the map. As discussed previously, the method used to remove low-frequency modes leaves the mean of the map and the point source kernel equal to zero, and every mm-source adds both positive and negative flux to the map. This is demonstrated in the left panel of Figure 4.5, which shows the histogram of flux density values in the AzTEC/GOODS-S map (with Poisson error bars). The dashed curve shows the distribution of pixel fluxes averaged over 100 jackknifed noise realizations of this field, and is very Gaussian. The flux distribution in the real map on the other hand is skewed by the presence of mm-sources. While this effect makes the identification of individual galaxies challenging, we can use the distribution of flux values in the map to perform a fluctuation analysis, or more commonly referred to as a “\(p(d)\)” analysis, in order to determine the number counts distribution for this field. Using this technique on the AzTEC/GOODS-S map can potentially provide strong constraints on the SMG number counts at faint flux densities \(S_{1.1\text{mm}} < 1\text{ mJy}\) below the 1.1 mm confusion-limit.

The fluctuation analysis is carried out as follows: using a parametrized model of the number counts, we generate 100 simulated maps as described in Section 4.4.4 and compare the flux density distribution averaged over these simulated maps to that of the real GOODS-S map. For this single model, we calculate the comparison metric:
Figure 4.5. The histogram of flux density values in the AzTEC/GOODS-S map and the likelihood estimate over a grid in $S' - N_{3\text{mJy}}$ parameter space from a fluctuation analysis of the map. **Left:** The histogram of flux density values in the AzTEC/GOODS-S map (red). The dashed curve shows the distribution of flux values averaged over 100 noise realizations for this field, and is Gaussian distributed about zero. The solid curve shows the flux distribution averaged over fully simulated maps, populated according to the best-fit Schechter function model to the GOODS-S data. This demonstrates how a fluctuation analysis is used to determine the best model to the GOODS-S data. **Right:** A map of the likelihood values over the $S' - N_{3\text{mJy}}$ parameter space from the fluctuation analysis. The cross indicates the best-fit parameters to the data. The inner and outer contours indicate the 68.3% and 95.5% confidence regions, respectively. The error bars represent marginalized 68.3% confidence intervals on each parameter.
\[-\ln(L) = \sum_i m_i - d_i + d_i \cdot \ln(d_i/m_i) \quad (4.2)\]

where \(m_i\) represents the average number of pixels in the \(i^{th}\) flux density bin from the model and \(d_i\) represents the corresponding quantity for the GOODS-S map. This process is repeated over a grid in parameter space to find the minimum of the above metric, which occurs at the best-fit model. Minimizing this metric is equivalent to finding the maximum likelihood for the case that all histogram bins follow independent Poisson distributions. Note that we do not attempt to model effects of source clustering on the pixel flux distributions, since the clustering properties of the SMG population are not well known. This method is similar in principle to the parametric frequentist approach used by Perera et al. (2008) to determine number counts for the AzTEC/GOODS-N survey; however, here we consider the full flux density histogram in order to extract information about the faint source population.

For this analysis we choose a Schechter function model given by:

\[
\frac{dN}{dS} = N_{3\text{mJy}} \left( \frac{S}{3 \text{ mJy}} \right)^{\alpha+1} \exp \left( \frac{-(S - 3 \text{ mJy})}{S'} \right) \quad (4.3)
\]

where \(\frac{dN}{dS}\) is the differential number counts as a function of intrinsic 1.1 mm flux density \(S\), and \((S', N_{3\text{mJy}}, \alpha)\) are the free parameters. While there are many forms of the Schechter function published in the literature, we prefer this form because it reduces the degeneracies between the three parameters, and it has been used in the number counts analysis of several previous AzTEC surveys (Perera et al., 2008; Austermann et al., 2009a,b), making it straightforward to compare the results. We prefer a Schechter function model over that of a single power-law because it allows for a natural steepening of the counts at high flux densities, which has been confirmed by large-area surveys at submm/mm wavelengths (Coppin et al., 2006; Austermann et al., 2009a) – though we are unlikely to see this steepening in the GOODS-S number counts given the small survey area. To simplify parameter space, we fix \(\alpha = -2\): a
value that is consistent with estimates from previous surveys (e.g. Coppin et al., 2006; Perera et al., 2008; Austermann et al., 2009a,b).

Since the Schechter function increases to infinity as $S$ goes to zero, we must assume some minimum flux density cutoff, $S_{\text{min}}$, for the population. A practical minimum flux limit is imposed by the data itself: at the flux density corresponding to where the number density of sources is $\sim 1$ per beam, adding fainter sources will not alter the flux density distribution in the map. Assuming the best-fit model to the AzTEC/SHADES data (Austermann et al., 2009a, which currently provides the tightest constraints on the blank-field 1.1 mm number counts), $S_{\text{min}} \sim 0.1$ mJy. While it is not known whether the number density of sources for the SMG population turns over and starts to decrease somewhere below 1 mJy, the counts at the faint-end of the 850 $\mu$m SCUBA galaxy population determined from lensing cluster surveys (e.g. Cowie et al., 2002; Smail et al., 2002; Knudsen et al., 2006, 2008) continue to rise out to $S_{850\mu m} \approx 0.2$ mJy, giving some reassurance that a 1.1 mm flux cutoff of $S_{\text{min}} = 0.1$ mJy is reasonable. We use $S_{\text{min}} = 0.1$ mJy in generating all simulated maps discussed in this paper; however, we have tested values ranging from $S_{\text{min}} = 0.05 - 0.3$ mJy and have found that this does not affect the results from the fluctuation analysis.

Using 0.1 mJy bins for the flux histograms, we restrict the data–model comparison to bins with $\geq 10$ pixels on average (flux densities of $-2.8$ to 5.5 mJy). The resulting best-fit parameters are $(S', N_{3\text{mJy}}) = (1.30^{+0.19}_{-0.25}$ mJy, $160.0^{+27}_{-28}$ mJy$^{-1}\text{deg}^{-2}$). The flux distribution for this best-fit model is shown as the solid curve in the left panel of Figure 4.5. The likelihood values for the $S' - N_{3\text{mJy}}$ parameter space are shown in the right panel of Figure 4.5, with the best-fit parameters indicated by the cross. Due to the strong bin-to-bin correlations, it is not possible to determine the errors on the best-fit parameters analytically. Instead, we determine the errors statistically through simulation by generating 600 fully simulated maps populated assuming the best-fit Schechter function model to the real GOODS-S map (including Poisson deviations),
Table 4.3. The best-fit parameters for models to the AzTEC/GOODS-S number counts. The method used is listed in the first column: FA = fluctuation analysis, and BM = Bayesian method. The errors on the best-fit parameters represent marginalized 68.3% confidence intervals. When an error is not listed, the parameter was fixed to the given value.

<table>
<thead>
<tr>
<th>Method</th>
<th>Model</th>
<th>$S'$ (mJy)</th>
<th>$N_{3mJy}$ (mJy$^{-1}$deg$^{-2}$)</th>
<th>$\alpha$</th>
</tr>
</thead>
<tbody>
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<td>FA</td>
<td>Eqn 4.3</td>
<td>1.30$^{+0.19}_{-0.25}$</td>
<td>160.$^{+27.}_{-28.}$</td>
<td>$-2.0$</td>
</tr>
<tr>
<td>BM</td>
<td>Eqn 4.3</td>
<td>1.47$^{+0.40}_{-0.25}$</td>
<td>131.$^{+30.}_{-20.}$</td>
<td>$-2.0$</td>
</tr>
<tr>
<td>FA</td>
<td>Eqn 4.4</td>
<td>$--$</td>
<td>90.$^{+20.}_{-18.}$</td>
<td>$-3.70^{+0.18}_{-0.11}$</td>
</tr>
<tr>
<td>BM</td>
<td>Eqn 4.4</td>
<td>$--$</td>
<td>107.$^{+30.}_{-10.}$</td>
<td>$-3.35^{+0.25}_{-0.15}$</td>
</tr>
</tbody>
</table>

and then performing the same fluctuation analysis on these simulated maps. The distribution of best-fit parameters from these simulated maps are used to determine the 68.3% and 95.5% confidence intervals (contours in Figure 4.5). The errors given for $S'$ and $N_{3mJy}$ above (and shown as error bars in Figure 4.5) represent the marginalized 68.3% confidence intervals on each parameter.

The ability to recover the input number counts determined from the fully simulated maps verifies the reliability of this fluctuation analysis method. The best-fit model to the actual GOODS-S data is listed in the first row of Table 4.3, and the differential number counts from this fluctuation analysis is shown in Figure 4.6 as the thick solid curve (best-fit) and dark shaded region (68.3% confidence interval). These results are also shown in Figure 4.7 for a comparison with other surveys.

While potentially providing tight constraints on the source counts of the SMG population, this fluctuation analysis relies strongly on the accuracy of our noise realizations and the point source kernel, and is sensitive to the assumed number counts model. To demonstrate this, we carry out a fluctuation analysis on the GOODS-S data assuming instead a single power-law model for the number counts, which is given by

$$
\frac{dN}{dS} = N_{3mJy} \left( \frac{S}{3 \text{ mJy}} \right)^{\alpha+1}.
$$

(4.4)
Figure 4.6. The differential number counts for the AzTEC/GOODS-S field using various methods and models. The solid curve and dark shaded region indicate the best-fit model and 68.3% confidence interval from the fluctuation analysis, assuming a Schechter function model. The dashed curve and light shaded region indicate the best-fit model and 68.3% confidence interval from a fluctuation analysis assuming a single power-law model. The red squares show the Bayesian-extracted number counts and 68.3% confidence intervals determined in Section 4.5.2. The orange slanted (green horizontal) hatching shows the 68.3% confidence interval for a fit to the Bayesian-extracted counts, assuming a Schechter function (power-law) model for the population. The horizontal dashed line shows the survey limit, where the number counts will Poisson deviate to 0 mJy$^{-1}$deg$^{-2}$ 31.7% of the time given the area of the GOODS-S survey.
We chose this functional form to make both parameters easily comparable to those from the Schechter function model, since \(N_{3\text{mJy}}\) gives the differential number counts at 3 mJy, and \(\alpha\) represents the power-law dependence at low flux densities. The best-fit parameters are listed in the third row of Table 4.3, and the best-fit model and 68.3% confidence interval are shown as the dashed curve and light shaded region in Figures 4.6 and 4.7. The best-fit values of \(N_{3\text{mJy}}\) for the two different models are only marginally consistent, and the best-fit power-law index \((\alpha + 1 = -2.7)\) is significantly steeper than that assumed for the Schechter function model \((\alpha + 1 = -1.0)\). Comparing the two models in Figure 4.6, they disagree significantly at \(S \sim 2\) mJy, where supposedly the tightest constraints can be placed on the number counts. One must thus exercise caution when interpreting results from this fluctuation analysis, as it inherently assumes that the model provides a good representation of the source counts.

### 4.5.2 Bayesian Estimation

The semi-Bayesian method introduced by Coppin et al. (2005, 2006) to extract number counts from submm/mm surveys is now widely used due to its appropriate handling of various survey biases, and it has been extensively tested and validated using previous AzTEC data-sets (Perera et al., 2008; Austermann et al., 2009a,b). Since this method is described in detail in the aforementioned papers we only briefly summarize the steps here.

The raw source counts from submm/mm surveys suffer from three main biases: the “flux-boosting” effect described in Section 4.4.3, contamination from false positives, and incompleteness. To account for the first two effects, we generate posterior flux distributions (PFDs), \(p(S_i|S_m, \sigma_m)\) (where \(S_i\) is the intrinsic flux density of the source, \(S_m\) is the measured flux density, and \(\sigma_m\) is the error on the measured flux density), for each source candidate assuming some prior model for the SMG number counts.
(see Section 3.5.1). These PFDs are then randomly sampled (with replacement) to determine intrinsic flux densities for the sources, and these fluxes are binned to calculate differential and cumulative number counts. This process is repeated 20,000 times to adequately sample the number counts distribution. We also include sample variance by Poisson deviating the number of sources sampled in each of the 20,000 iterations. Since the PFD for each source candidate includes a non-negligible probability that the intrinsic flux density is $S_i < 0$ mJy, this procedure inherently accounts for false positives.

To extract source counts from the AzTEC/GOODS-S map, we use the best-fit Schechter function model determined from the fluctuation analysis as the prior distribution to generate PFDs for the source candidates. We sample all source candidates where the probability of the source having a flux density less than zero is $p(S_i < 0|S_m, \sigma_m) \leq 0.05$, which corresponds to $S/N \gtrsim 2.8$ (actually depends on both $S_m$ and $\sigma_m$) for a total of 54 source candidates. At face value, this includes a significant number of low S/N source candidates, and consequently a high number of false positives. However, as discussed in Section 4.4.4, the number of false positives at this S/N threshold is expected to be quite low ($\sim 3\%$) based on realistic simulations of the underlying source population. Austermann et al. (2009a) tested various limiting thresholds for $p(S_i < 0|S_m, \sigma_m)$ using several AzTEC datasets and found that any variations in the resulting number counts are much smaller than the formal 68.3% uncertainties. They found that for accurate PFDs, the $p(S_i < 0|S_m, \sigma_m)$ limiting threshold does not greatly affect the resulting number counts (provided source confusion is not an issue), and that using a higher limiting threshold supplies more information (due to increased survey completeness at faint flux densities) without introducing significant biases. We have verified that the PFDs for GOODS-S source candidates with $S/N \geq 2.8$ are accurate to $\lesssim 1\%$ at $S_i \geq 0.5$ mJy following the
simulations described in Austermann et al. (2009a,b), further justifying the use of a \( p(S_i < 0|S_m, \sigma_m) \leq 0.05 \) limiting threshold in this analysis.

The raw number counts must also be corrected for incompleteness. In previous implementations of the semi-Bayesian method on AzTEC data-sets (Perera et al., 2008; Austermann et al., 2009a,b), survey completeness was estimated by the recovery rate of synthetic point sources with known intrinsic flux densities inserted into pure noise realizations one at a time. However as explained in Section 4.4.5, we have found that this method overestimates the survey completeness for the AzTEC/GOODS-S field, since it does not account for confusion noise (the effect here is even stronger than that shown in Figure 4.3, since we are now including lower \( S/N \) sources in the number counts analysis). Using a pure noise completeness estimate would consequently underestimate the number counts in this field. We instead estimate the survey completeness through fully simulated maps as described in Section 4.4.5, where the simulated maps are populated according to the number counts distribution given by the assumed prior. Since we are using an “ideal” prior determined from the fluctuation analysis of this field, we are confident that this provides a good completeness estimate for the correction of the raw number counts.

The 1.1 mm differential number counts for the GOODS-S field determined from the Bayesian method are shown in Figure 4.6 (red squares), and both the differential and cumulative number counts are shown in Figure 4.7 and are listed in Table 4.4. The number counts are calculated from the mean number of sources in each flux bin (with bin-size = 1 mJy) over the 20,000 iterations, and the errors represent the 68.3% confidence intervals calculated from the distribution in the counts across those iterations. For the differential number counts, the flux densities in Table 4.4 are the effective bin centers weighted by the assumed prior. The number counts from this method are highly correlated since they are estimated by averaging over many realizations of the number counts bootstrapped off the same source catalog. The
Table 4.4. The differential and cumulative number counts for the AzTEC/GOODS-S field. These are calculated using the Bayesian method described in Section 4.5.2. The errors indicate 68.3% confidence intervals.

<table>
<thead>
<tr>
<th>Flux Density (mJy)</th>
<th>dN/dS (mJy$^{-1}$deg$^{-2}$)</th>
<th>Flux Density (mJy)</th>
<th>N(&gt;S) (deg$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.85</td>
<td>1892$^{+453}_{-554}$</td>
<td>0.50</td>
<td>2631$^{+478}_{-502}$</td>
</tr>
<tr>
<td>1.90</td>
<td>461$^{+97}_{-116}$</td>
<td>1.50</td>
<td>739$^{+117}_{-132}$</td>
</tr>
<tr>
<td>2.91</td>
<td>170$^{+46}_{-57}$</td>
<td>2.50</td>
<td>279$^{+57}_{-62}$</td>
</tr>
<tr>
<td>3.92</td>
<td>58$^{+23}_{-33}$</td>
<td>3.50</td>
<td>109$^{+33}_{-41}$</td>
</tr>
<tr>
<td>4.92</td>
<td>28$^{+14}_{-22}$</td>
<td>4.50</td>
<td>50$^{+23}_{-31}$</td>
</tr>
<tr>
<td>5.92</td>
<td>17$^{+8}_{-17}$</td>
<td>5.50</td>
<td>22$^{+7}_{-21}$</td>
</tr>
</tbody>
</table>

Table 4.5. The covariance matrix for the differential number counts for the AzTEC/GOODS-S field. The units are in mJy$^{-2}$deg$^{-4}$.

<table>
<thead>
<tr>
<th>Flux Density (mJy)</th>
<th>0.85</th>
<th>1.90</th>
<th>2.91</th>
<th>3.92</th>
<th>4.92</th>
<th>5.92</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.85</td>
<td>254800</td>
<td>37340</td>
<td>3559</td>
<td>82</td>
<td>-79</td>
<td>11</td>
</tr>
<tr>
<td>1.90</td>
<td>11420</td>
<td>2835</td>
<td>345</td>
<td>8</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>2.91</td>
<td>2623</td>
<td>848</td>
<td>73</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.92</td>
<td>808</td>
<td>353</td>
<td>27</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.92</td>
<td>366</td>
<td>127</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.92</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>230</td>
</tr>
</tbody>
</table>

covariance matrices for the differential and cumulative number counts are listed in Tables 4.5 and 4.6, respectively.

The Bayesian-extracted number counts agree within the 1σ errors with the best-fit Schechter function model from the fluctuation analysis. However, the number counts in the two lowest flux density bins (0.5 – 1.5 mJy and 1.5 – 2.5 mJy) are low compared to the best-fit curve from the fluctuation analysis, while the number counts in the highest bin (5.5 – 6.5 mJy) are high. This may arise from a systematic bias in the Bayesian-extraction method due to source blending, since this technique does not account for the possibility that an individually detected source is the summed flux density of two or more galaxies. This would indeed result in the apparent bias seen here, as the number counts would be overestimated at high flux densities and
Table 4.6. The covariance matrix for the cumulative number counts for the AzTEC/GOODS-S field. The units are in \text{deg}^{-4}.

<table>
<thead>
<tr>
<th>Flux Density (mJy)</th>
<th>0.50</th>
<th>1.50</th>
<th>2.50</th>
<th>3.50</th>
<th>4.50</th>
<th>5.50</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50</td>
<td>271300</td>
<td>16060</td>
<td>4350</td>
<td>1478</td>
<td>659</td>
<td>307</td>
</tr>
<tr>
<td>1.50</td>
<td>15580</td>
<td>4144</td>
<td>1470</td>
<td>650</td>
<td>300</td>
<td></td>
</tr>
<tr>
<td>2.50</td>
<td>4123</td>
<td>1486</td>
<td>667</td>
<td>293</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.50</td>
<td></td>
<td>1471</td>
<td>667</td>
<td>297</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.50</td>
<td></td>
<td></td>
<td>670</td>
<td>301</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.50</td>
<td></td>
<td></td>
<td></td>
<td>297</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

underestimated at low flux densities. We have checked for this possible bias in the Bayesian method by running this analysis on source catalogs extracted from 600 fully simulated maps populated according to the best-fit model from the fluctuation analysis. Since in this case we know the exact form of the source counts input into each map, we can search for such effects in the output number counts. We find that the output differential number counts for these simulated maps do indicate that this bias due to source blending is present in the data: for the 5.5 \text{–} 6.5 \text{mJy} flux density bin, the extracted number counts are higher than the input number counts for 65\% of the simulated maps, while for the 0.5 \text{–} 1.5 \text{mJy} bin, the extracted counts are lower than the input counts for 60\% of the simulated maps. However, at all flux densities, the extracted number counts agree with the input number counts within their 1\sigma (2\sigma) errors at least 86\% (96\%) of the time, so this bias is small compared to the formal Poisson errors.

To verify that the Bayesian-extracted number counts are insensitive to the assumed prior, we reran this procedure on the AzTEC/GOODS-S map using a prior distribution that is consistent with a fit to the number counts from the AzTEC/SHADES survey: \( (S', N_{3mJy}, \alpha) = (1.11 \text{ mJy}, 153 \text{ mJy}^{-1}\text{deg}^{-2}, -2.0) \). We find that the extracted numbers counts using these two different priors agree within 4\% at flux densities \( \geq 1.5 \text{ mJy} \). For the lowest flux bin of 0.5 \text{–} 1.5 \text{mJy}, the results agree within
19%, i.e. well within the formal 1σ error. This demonstrates that the results from this technique are robust given a reasonable assumption for the prior number counts distribution. For this reason, we can fit these number counts to various models.

For a given model, we fit to each of the 20,000 iterations separately as the flux density bins for a given iteration are uncorrelated, and we use the distribution of best-fit parameters to determine the most likely values and their confidence intervals. The results of a fit to the GOODS-S differential number counts assuming a Schechter function model (Equation 4.3) and a power-law model (Equation 4.4) are given in rows 2 and 4 of Table 4.3 and are shown in Figure 4.6 as the hatched regions, which indicate the 68.3% confidence intervals. The fits to the Bayesian-extracted counts are in good agreement with the results from the fluctuation analysis for a given model. To compare the two models, we compute the χ² metric given by

\[ \chi^2 = (d - m)^T W (d - m) \]  \hspace{1cm} (4.5)

where \( d \) is the row-vector containing the differential number counts from the Bayesian method, \( W \) is the corresponding weight matrix calculated from the inverse of the covariance matrix, and \( m \) is the model number counts evaluated at the same flux density bins as \( d \). For the best-fit Schechter function to the Bayesian-extracted number counts, \( \chi^2 = 0.84 \). This model provides a better fit to the data than the single power-law model, for which \( \chi^2 = 5.4 \). Note that since the errors are not Gaussian-distributed, this metric is not expected to follow the χ²-distribution; we use this metric simply to compare the relative goodness-of-fit for these two models.

### 4.5.3 Comparison with Results from SCUBA Lensing Cluster Surveys

The AzTEC/GOODS-S and South Ecliptic Pole (SEP, Hatsukade et al., 2009) blank-field surveys currently provide the only constraints on the 1.1 mm number counts at \( S < 1 \) mJy. For comparison, none of the existing blank-field SCUBA surveys
Figure 4.7. The differential and cumulative number counts from the AzTEC survey of GOODS-S. Left: The differential number counts from the AzTEC/GOODS-S survey (black squares), compared with those determined from AzTEC surveys of other fields, including: GOODS-N (upside-down green triangles; Perera et al., 2008), COSMOS (orange circles; Austermann et al., 2009b), SHADES (red stars; Austermann et al., 2009a), and SEP07 (cyan triangles) and SEP08 (blue triangles; Hatsukade et al., 2009). All error bars represent 68.3% confidence intervals on the Bayesian-extracted counts. The solid (dashed) curve and dark (light) shaded region indicate the best-fit Schechter function (power-law) model and 68.3% confidence region from a fluctuation analysis of the GOODS-S map (Section 4.5.1). The horizontal dashed line shows the survey limit, where the number counts will Poisson deviate to 0 mJy$^{-1}\text{deg}^{-2}$ 31.7% of the time given the area of the GOODS-S survey. Right: The cumulative number counts from the AzTEC/GOODS-S survey and AzTEC surveys of other fields. For comparison, the number counts from SCUBA 850 $\mu$m lensing cluster surveys are shown with smaller symbols: green triangles – Cowie et al. (2002, C02a); blue squares – Smail et al. (2002, S02); upside-down orange triangles – Chapman et al. (2002, C02b); and black circles – Knudsen et al. (2008, K08). All 850 $\mu$m counts have been scaled to 1.1 mm assuming a simple flux ratio scaling of $S_{850\mu m}/S_{1.1\text{mm}} = 1.8$. 
constrain the 850 µm counts to comparatively faint flux densities ($S_{850\mu m} \lesssim 2$ mJy): the deepest (e.g. Hughes et al., 1998; Eales et al., 2000) are too small in area to provide statistically significant samples of faint SMGs, while the large-area surveys (e.g. Borys et al., 2003; Coppin et al., 2006) do not reach sufficient depths to probe such faint sources. The most significant constraints on the $S_{850\mu m} \lesssim 2$ mJy number counts come from SCUBA lensing cluster surveys, where massive foreground clusters are used to probe faint background SMGs via gravitational lensing (e.g. Smail et al., 2002; Cowie et al., 2002; Chapman et al., 2002; Knudsen et al., 2006, 2008). This is a powerful technique for detecting intrinsically faint high-redshift SMGs and for estimating their source counts at low flux densities, as the foreground clusters magnify both the flux of the background sources (by factors of typically $2 - 3$) and the area in the source-plane, effectively decreasing the survey confusion-limit that hinders the sensitivity of blank-field observations. With new constraints on the $S_{1.1\text{mm}} = 0.5$ mJy number counts from the AzTEC/GOODS-S and SEP surveys, this is the first time that the faint-end of the number counts determined from lensing cluster surveys can be compared to results from blank-fields. Given the small sample size from lensing cluster surveys, this comparison is limited to the cumulative number counts.

The number counts from four separate SCUBA lensing cluster surveys are shown in the right panel of Figure 4.7. To compare to our 1.1 mm results, we must scale the SCUBA counts to account for the difference in observing wavelengths. We assume here that SCUBA and AzTEC are sampling the same underlying population of submm/mm-bright galaxies, and that the difference in the observed number counts can be described by a simple flux scaling: $R = (S_{850\mu m}/S_{1.1\text{mm}})$. In principle, surveys at 1 mm may preferentially select sources at higher redshifts – or sources with colder dust temperatures – than surveys at 850 µm. While there is some evidence that 1 mm surveys select on average higher redshift galaxies than 850 µm surveys (Eales et al., 2003; Younger et al., 2007, 2009; Greve et al., 2008), other studies suggest that there
is no significant difference between the two populations (Greve et al., 2004; Ivison et al., 2005; Bertoldi et al., 2007). A recent source-to-source comparison of SCUBA and AzTEC sources in the GOODS-N field (Chapin et al., 2009) reveals that while the redshift distribution of 1.1 mm sources in that field peaks at a higher redshift than that of 850 µm sources (\(z = 2.7\) versus \(z = 2.0\)), the population is consistent with an average flux scaling with \(R = 1.8\). Also, the 850 µm (Borys et al., 2003) and 1.1 mm (Perera et al., 2008) number counts from the GOODS-N field are consistent assuming a flux scaling of \(R = 2.1 \pm 0.2\). This is equivalent to the expected flux ratio of a \(z = 2.5\) galaxy whose spectral energy distribution (SED) can be modeled as a single-component modified blackbody with \(T_d = 30\) K and emissivity index \(\beta = 1.5\).

As this model is consistent with the expected SEDs of local galaxies observed with the Infrared Astronomical Satellite (IRAS) and SCUBA (Dunne et al., 2000; Dunne & Eales, 2001) as well as the measured SEDs of several SMGs (Chapman et al., 2005; Kovács et al., 2006; Pope et al., 2006; Coppin et al., 2008), we start by using a simple scaling factor of \(R = 1.8\) for the purposes of comparing the number counts from the SCUBA lensing cluster surveys to the AzTEC/GOODS-S number counts.

The number counts from the lensing cluster surveys only marginally agree with and are systematically higher at all flux densities than the number counts from this survey, as well as those determined from other blank-fields observed with AzTEC (see Figure 4.7). We next fit for the value of \(R\) that minimizes the residuals between the SCUBA lensing cluster number counts and the best-fit model to the 1.1 mm number counts from the AzTEC/GOODS-S field. The best-fit values and 68.3% confidence errors for \(R\) determined from each of the four lensing cluster data-sets shown in Figure 4.7 are given in Table 4.7. We estimate \(R \geq 3.3\) for all lensing cluster surveys considered here, regardless of which model (Schechter function or power-law) we consider. Such high values of \(R\) are inconsistent with observed values for individual SMGs (where both 850 µm and 1.1 mm measurements are available) as
Table 4.7. The 850 µm to 1.1 mm flux ratio estimated by scaling the number counts from SCUBA lensing cluster surveys to the best-fit model to the AzTEC/GOODS-S number counts. The columns are: 1) reference for the lensing cluster survey (last row is the results for all four surveys combined; 2) best-fit flux ratio $R = S_{850\mu m}/S_{1.1\text{mm}}$ and 68.3% confidence interval assuming the Schechter function model for the GOODS-S number counts (Equation 4.3); and 3) best-fit flux ratio and 68.3% confidence interval assuming the power-law model for the GOODS-S number counts (Equation 4.4).

<table>
<thead>
<tr>
<th>Reference</th>
<th>$R$ (Schechter)</th>
<th>$R$ (Power-law)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cowie et al. (2002)</td>
<td>$5.6^{+0.9}_{-0.9}$</td>
<td>$3.5^{+0.4}_{-0.5}$</td>
</tr>
<tr>
<td>Smail et al. (2002)</td>
<td>$4.4^{+0.9}_{-0.8}$</td>
<td>$3.2^{+0.3}_{-0.4}$</td>
</tr>
<tr>
<td>Chapman et al. (2002)</td>
<td>$5.2^{+0.8}_{-0.7}$</td>
<td>$5.5^{+0.5}_{-0.5}$</td>
</tr>
<tr>
<td>Knudsen et al. (2008)</td>
<td>$3.3^{+0.4}_{-0.4}$</td>
<td>$3.3^{+0.4}_{-0.5}$</td>
</tr>
<tr>
<td>All</td>
<td>$4.0^{+0.3}_{-0.3}$</td>
<td>$3.5^{+0.2}_{-0.3}$</td>
</tr>
</tbody>
</table>

well as predicted values assuming SEDs and redshifts typical of this population. We note however that a surprisingly high value of $R = 2.5 \pm 0.1$ has been estimated from a similar scaling of the 850 µm and 1.1 mm number counts from the SCUBA and AzTEC/SHADES surveys (Austermann et al., 2009a). If 1.1 mm surveys are tracing a population of galaxies with either higher redshifts or colder dust temperatures than those detected at 850 µm, we would expect this flux ratio to be lower than that measured from individual sources. The high value of $R$ measured from scaling the SHADES number counts is likely due to systematics caused by small differences in the number counts analyses or calibration, so we consider this an upper limit to the true flux ratio. Estimates of $R$ from scaling the 850 µm lensing cluster number counts to the best-fit model to the AzTEC/GOODS-S data-set represent $\gtrsim 2\sigma$ deviations from this upper limit of $R = 2.5$ from the SHADES results, implying that even greater systematics exist in the lensing cluster number counts. We note that this is consistent with results from blank-field 850 µm surveys: the cumulative number counts at $S_{850\mu m} > 2$ mJy from lensing cluster surveys are systematically higher than those from large-area blank-field SCUBA surveys (e.g. Borys et al., 2003; Webb et al., 2003; Scott et al., 2006; Coppin et al., 2006).
There are several potential biases in the number counts extraction from lensing cluster surveys which may systematically bias the number counts high. While it is true that constructing number counts from such surveys requires detailed mass models of the lensing clusters, any errors in estimating magnification factors for source flux densities are compensated by equivalent errors in the source-plane area, so it is difficult to systematically bias the counts high due to errors in the cluster mass model (Knudsen et al., 2008). It is possible that the counts are high due to contamination from cluster members; however, most groups have tried to identify cluster candidates and exclude them from their samples. All of the lensing cluster surveys considered here include sources detected with low significance ($S/N \geq 3.0$), and thus potentially include a significant number of false positives which would bias the number counts high. However, due to the small survey areas, the number of false positives at $S/N \geq 3.0$ should be negligible for these surveys. The errors on the cumulative counts for the lensing cluster surveys are dominated by Poisson noise due to the limited survey areas ($\leq 35$ arcmin$^2$ in the source-plane) and small sample sizes. If SMGs cluster strongly on small angular scales, the apparent bias in lensing cluster surveys may simply be the result of cosmic variance. However, none of the lensing cluster surveys fully account for the flux-boosting effect described in Sections 3.5.1 and 4.4.3, and this is most likely the dominant systematic that is causing the discrepancies between the number counts from these surveys and those determined from blank-field surveys at 850 $\mu$m and 1.1 mm.

### 4.5.4 Comparison with Other 1.1 mm Surveys

The differential and cumulative number counts from other 1.1 mm blank-field surveys are shown in Figure 4.7 for comparison. These include the AzTEC surveys of GOODS-N (Perera et al., 2008), COSMOS (Chapter 3; Scott et al., 2008; Austermann et al., 2009b), and SHADES (Austermann et al., 2009a) taken on the JCMT, and
the surveys of two separate regions in the SEP taken in 2007 and 2008 (referred to hereafter as the SEP07 and SEP08 fields, Hatsukade et al., 2009) taken on the ASTE. The SHADES data-set consists of two separate regions of sky – the Lockman Hole-East (LH-E) and the Subaru/XMM-Newton Deep Field (SXDF) – and covers a total area of 0.67 deg², making it the largest blank-field survey at 1.1 mm published to date. Compared to SHADES, the GOODS-N, SEP07, and COSMOS (see Section 3.8) fields appear somewhat over-dense, while the number counts from GOODS-S and SEP08 are consistent with those from SHADES. We present a combined number counts analysis from all of these blank-field AzTEC surveys in Chapter 5.

4.6 Comparison with $BzK$-Selected Galaxies

A two-color selection based on $B$-, $z$-, and $K$-photometry has recently been used to select actively star-forming galaxies at $1.4 \leq z \leq 2.5$ in $K$-selected samples of galaxies nearly independent of their dust reddening (Daddi et al., 2004). A sample of these $BzK$ galaxies with $K_{\text{Vega}} < 22$ have been identified in the GOODS-S field (Daddi et al., 2007a). These $BzK$s have an average SFR of 70 M$_\odot$/yr and high stellar masses of $10^{10.5-11.5}$ M$_\odot$. Given their large sizes, asymmetric merger-like morphologies, and hints of strong clustering properties, $BzK$s could be the precursors to passively evolving elliptical galaxies observed at $z = 0$, and this population is likely to overlap to some degree with SMGs. Since the space density of SMGs is $10-100$ times lower than that of $BzK$s (Daddi et al., 2004) and SMGs are known to have comparatively high SFRs of $\sim 1000$ M$_\odot$/yr, SMGs may be an extreme subset of the $BzK$ population. In this Section, we study the average 1.1 mm properties of $BzK$-selected galaxies in GOODS-S through a stacking analysis, where we calculate the average 1.1 mm flux at the locations of $BzK$s in this field.

In the left panel of Figure 4.8, we show the stacked 1.1 mm flux from the full catalog of star-forming $BzK$ galaxies (total of 954) in GOODS-S. The average 1.1 mm
Figure 4.8. Stacked 1.1 mm flux at the locations of star-forming $BzK$-selected galaxies in the GOODS-S field. **Left:** stack on all star-forming $BzK$s; **Center:** stack on $BzK$s with a mid-IR excess; **Right:** stack on $BzK$s without a mid-IR excess. The images are shown on the same color scale which ranges from −80 µJy to 500 µJy.

Flux is estimated from the stacked image at zero offset from the $BzK$ positions and is 152 ± 27 µJy. To evaluate the significance of this detection, we generate 4,000 random catalogs, where each consists of 954 random positions covering the extent of the $BzK$ survey. We find that the measured 1.1 mm flux from stacking on the $BzK$ positions is always greater than that measured from stacking on random positions. From the distribution of 1.1 mm fluxes measured from the 4,000 random catalogs, this detection represents a $5.0\sigma$ deviation from the mean, confirming the sensitivity of this measurement to the average 1.1 mm emission of the $BzK$ population.

Daddi et al. (2007a,b) identified a group of $BzK$-selected galaxies whose SFRs estimated from their observed 24 µm emission ($\text{SFR}_{24\mu m}$) are overestimated by a factor of $\geq 3$ compared to their SFRs estimated from their extinction-corrected ultraviolet (UV) luminosities ($\text{SFR}_{\text{UV,corr}}$) as well as other SFR tracers, including their far-IR (FIR), submm, and radio emission. The median SED of these mid-IR excess $BzK$s compared to that of $BzK$s where $\text{SFR}_{24\mu m} \approx \text{SFR}_{\text{UV,corr}}$ also shows an excess of emission in all four IRAC bands from 3.6 – 8.0 µm and is consistent with the presence of warm dust heated by active galactic nuclei (AGN; Daddi et al., 2007b).
Table 4.8. Results from a stacking analysis on the AzTEC/GOODS-S map at the locations of $BzK$-selected galaxies. The columns are as follows: 1) the $BzK$s used in the stack, where “All” means the full star-forming $BzK$ catalog, “mid-IRX” refers to $BzK$s with a mid-IR excess, and “no mid-IRX” refers to $BzK$s without a mid-IR excess; 2) the number of $BzK$s in each group; 3) the 1.1 mm flux and noise of the stacked map at zero offset from the $BzK$ positions; 4) probability that the stacked 1.1 mm flux at $BzK$ positions is greater than that measured from stacking at random positions; and 5) the significance of the detection determined from the number of standard deviations from the mean stacked flux using random positions.

<table>
<thead>
<tr>
<th>$BzK$s</th>
<th>$N_{BzK}$</th>
<th>$S_{1.1\text{mm}}$ (µJy)</th>
<th>$P(&gt;S_{\text{random}})$</th>
<th>$N\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>954</td>
<td>152±27</td>
<td>1.00</td>
<td>5.0</td>
</tr>
<tr>
<td>Mid-IRX</td>
<td>104</td>
<td>492±80</td>
<td>1.00</td>
<td>5.4</td>
</tr>
<tr>
<td>No mid-IRX</td>
<td>316</td>
<td>62±46</td>
<td>0.85</td>
<td>1.0</td>
</tr>
</tbody>
</table>

While these galaxies are not individually detected at X-ray wavelengths, the hardness of their stacked X-ray spectrum is consistent with that of heavily obscured AGN. We estimate the average 1.1 mm flux of star-forming $BzK$ galaxies with a mid-IR excess (total of 104) versus that of $BzK$s identified as having no mid-IR excess (total of 316) by stacking separately on these two subgroups. We find that $BzK$s with a mid-IR excess have an average 1.1 mm flux of 492±80 µJy (center panel of Figure 4.8); on the other hand, we do not significantly detect the 1.1 mm emission from $BzK$s without a mid-IR excess (62 ± 46 µJy, right panel of Figure 4.8). The stacked 1.1 mm flux at the positions of mid-IR excess $BzK$s is a 5.4σ deviation from the mean measured from 4,000 catalogs of random positions. The stacked 1.1 mm flux for $BzK$s with no mid-IR excess is greater than that measured from random position catalogs only 85% of the time (a 1σ deviation). These results are summarized in Table 4.8. Combined with the results from stacking on the full $BzK$ catalog, we conclude that mid-IR excess $BzK$s dominate the stacked signal, and that they are on average $>3.5$ times brighter at 1.1 mm than $BzK$s without a mid-IR excess (assuming a 3σ upper limit on the 1.1 mm flux for $BzK$s with no mid-IR excess).
Daddi et al. (2007b) find that the mid-IR excess sources preferentially reside in $BzK$ s with larger than average stellar masses. Since there is also a strong correlation between stellar mass and $\text{SFR}_{\text{UV,corr}}$ for the full sample of $BzK$s, the fraction of sources with a mid-IR excess likewise increases with SFR. This appears to be consistent with our results: the average 1.1 mm emission—a good tracer of SFR—from $BzK$s with a mid-IR excess is larger than that of $BzK$s without a mid-IR excess. However, Daddi et al. (2007b) find that the average SFR of $BzK$s showing a mid-IR excess ($\approx 90$ M$_{\odot}$/yr) is only $30 - 40\%$ higher than normal $BzK$s ($\approx 70$ M$_{\odot}$/yr) based on the estimates from their extinction-corrected UV luminosities. On average, the $\text{SFR}_{\text{UV,corr}}$ for these galaxies agree with the estimates from their radio emission ($\text{SFR}_{1.4 \text{GHz}}$), so this is unlikely due to a misidentification of a mid-IR excess caused by underestimating the extinction. Similarly, by stacking on the 70 $\mu$m and 850 $\mu$m maps at the locations of $BzK$ galaxies in the GOODS-N field, estimates of the average SFR based on their FIR/submm emission suggest that mid-IR excess galaxies have only marginally higher SFRs than those of galaxies without a mid-IR excess (though these stacking results give only $\sim 3\sigma$ detections).

Using the 1.1 mm emission from $BzK$s determined from our stacking analysis, we estimate their average FIR luminosity ($L\text{_{FIR}} = L_{8-1000\mu m}$) using an average redshift of $z = 2.1$ (1.9) for mid-IR excess (normal) $BzK$s and assuming a modified black-body SED with a dust temperature of $T_d = 40$ K and emissivity index $\beta = 1.6$ up to $\nu = 4500$ GHz, and then a power-law SED with spectral index $\alpha = -1.7$ to model the hotter dust components on the Wien side of the spectrum. This model (see Laurent et al., 2005) provides a reasonable fit to a composite SED from nearby $\text{IRAS}$ galaxies, high-redshift SMGs, and high-redshift AGNs (Blain et al., 2002, and references therein). We then use the relationship between FIR luminosity and SFR from Kennicutt (1998) to calculate the average SFR of $BzK$s with a mid-IR excess and the average SFR of all $BzK$s in the GOODS-S field, which are $180$ M$_{\odot}$/yr and $60$ M$_{\odot}$/yr,
respectively. The SFR estimated from the average 1.1 mm emission (SFR$_{1.1\text{mm}}$) from all $BzK$s is consistent with SFR$_{\text{UV,corr}}$; however, we find that the SFR$_{1.1\text{mm}}$ from $BzK$s with a mid-IR excess is roughly three times larger, in contrast with the results from Daddi et al. (2007b).

We next estimate the average SFR from these galaxies using their radio emission by stacking the 1.4 GHz map at the $BzK$ positions. We assume a power-law SED with $\alpha = -0.8$ for the radio emission to estimate the rest-frame 1.4 GHz luminosity ($L_{1.4\text{GHz}}$), and we use the local FIR to radio relation from Condon (1992) to convert $L_{1.4\text{GHz}}$ to $L_{\text{FIR}}$ in order to calculate the SFR. This SFR estimated from the average radio luminosity (SFR$_{1.4\text{GHz}}$) is in good agreement with the SFR$_{1.1\text{mm}}$ from our stacking analysis: 165 M$_{\odot}$/yr for $BzK$s with a mid-IR excess and 50 M$_{\odot}$/yr for normal $BzK$s. Based on the agreement between these different estimates of the SFR, we conclude that the apparent mid-IR excess in some $BzK$s may result from underestimating the extinction (and thus SFR$_{\text{UV,corr}}$) in these galaxies, rather than arising from warm dust emission due to AGN activity. Our results seem inconsistent with those of Daddi et al. (2007b), who claim that on average SFR$_{\text{UV,corr}} \approx$ SFR$_{1.4\text{GHz}}$ for all $BzK$s, including those with a mid-IR excess. However, 10 – 15% of their mid-IR excess sources show a similar excess in their radio emission, and it is likely that the UV luminosity has been underestimated for a subset of these galaxies (Daddi et al., 2007a). It is possible that the 1.1 mm and 1.4 GHz signal from our stacking analyses on mid-IR excess $BzK$s is dominated by such sources. To study this possibility, we must consider the 1.1 mm and 1.4 GHz properties of individual $BzK$s with and without a mid-IR excess to avoid possible systematics caused by averaging the source properties. We will address this in a future analysis once we have identified secure multi-wavelength counterparts to the AzTEC SMGs in this field.
4.7 Contribution of Different Galaxy Populations to the Cosmic Infrared Background at 1.1 mm

Summing the deboosted 1.1 mm flux densities of the 41 $S/N \geq 3.5$ source candidates in the AzTEC/GOODS-S map, we measure an integrated flux of 1.5 Jy deg$^{-2}$ over the 0.075 deg$^2$ field. Comparing this to the total energy density in the CIB at 1.1 mm of $18 - 24$ Jy deg$^{-2}$ (Puget et al., 1996; Fixsen et al., 1998), we have resolved only $6 - 8\%$ of the CIB into individual galaxies. However, if we instead integrate the best-fit Schechter function model to the GOODS-S number counts down to 0 mJy, we estimate that we have resolved $6.3$ Jy deg$^{-2}$, or $26 - 35\%$, of the CIB at 1.1 mm with our AzTEC/GOODS-S survey. The fact that we do not resolve 100\% of the CIB through this integration implies that the best-fit Schechter function model to our data from $0.5$ mJy $< S_{1.1\text{mm}} < 6.5$ mJy significantly underestimates the 1.1 mm number counts of faint galaxies at $S_{1.1\text{mm}} < 0.5$ mJy.

We use a stacking analysis to estimate the fraction of the CIB at 1.1 mm that is resolved by the entire 1.4 GHz radio population. Stacking at the locations of $N = 222$ radio sources in this fields (up slightly from 219 radio sources used in the stacking analysis in Section 4.4.2, since we have shifted our AzTEC map to correct the astrometry), we calculate an average 1.1 mm flux density of $S_{1.1\text{mm, radio}} = 660 \pm 78 \, \mu$Jy. Assuming that each of the radio sources distributed over an area $A = 0.075$ deg$^2$ has a flux density of $S_{1.1\text{mm, radio}}$, the radio population has a total integrated flux of $N \cdot S_{1.1\text{mm, radio}}/A = 1.9$ Jy deg$^{-2}$, resolving $8 - 11\%$ of the CIB.

We next estimate the contribution to the CIB at 1.1 mm from MIPS 24 \( \mu \)m-selected sources using a similar stacking analysis. The average flux density from 1185 24 \( \mu \)m sources distributed over a 0.068 deg$^2$ area is $S_{1.1\text{mm, 24}\mu\text{m}} = 290 \pm 26 \, \mu$Jy. The total integrated flux from 24 \( \mu \)m sources at 1.1 mm is $5.0$ Jy deg$^{-2}$, or $21 - 28\%$ of the total CIB. This is similar to the fraction of the CIB at 850 \( \mu \)m resolved by 24 \( \mu \)m sources ($29 - 37\%$) in the SCUBA/GOODS-N field (Wang et al., 2006). In
contrast, a stacking analysis of 24 $\mu$m sources with the BLAST maps of GOODS-S at 250, 350, and 500 $\mu$m suggests that the full intensity of the CIB at these shorter wavelengths is resolved by sources selected at 24 $\mu$m (Devlin et al., 2009; Marsden et al., 2009). This demonstrates the existence of a significant population of higher-redshift ($z \gtrsim 3$) dust-obscured galaxies that are (statistically speaking) missed by current $\lambda \lesssim 500$ $\mu$m surveys, but account for $\approx 2/3$ of the CIB at longer wavelengths.

We calculate a total integrated flux of 3.1 Jy deg$^{-2}$, or 13 – 17% of the CIB at 1.1 mm, from star-forming $BzK$-selected galaxies from the stacking analysis presented in Section 4.6. This is comparable to the fraction of the 850 $\mu$m CIB resolved by $BzK$s (10 – 15%) in the SCUBA/SHADES field (Takagi et al., 2007). These star-forming $BzK$s appear to contribute a larger fraction to the CIB at BLAST wavelengths: 32%, 34%, and 42% at 250, 350, and 500 $\mu$m, respectively (Marsden et al., 2009).

### 4.8 Conclusions

We imaged a 270 arcmin$^2$ field towards the GOODS-S region to a confusion-limited depth of $1\sigma \sim 0.6$ mJy using the AzTEC camera on the ASTE, making this one of the deepest surveys carried out to date at 1.1 mm. We detect 41 SMG candidates with $S/N \geq 3.5$, where at most two are expected to be false positives arising from noise peaks. This survey is 50% complete at 2.1 mJy and 95% complete at 3.5 mJy. We have demonstrated that the presence of confusion noise has significant consequences for the properties of the map and must be considered when accessing the survey completeness and expected number of false detections in the source catalog. From realistic simulations of the SMG population in this field, we estimate that 18% of the source candidates identified in the AzTEC/GOODS-S map are actually two or more mm-bright galaxies with comparable flux densities blended together due to the low angular resolution of the ASTE beam.
We have used two very different methods to estimate the SMG number counts in this field: a fluctuation analysis where we model the distribution of flux density values in the map, and a semi-Bayesian technique where the number counts are determined from sampling the PFDs from the catalog of SMGs. We have demonstrated that both methods are able to retrieve the correct number counts distribution from fully simulated data-sets. Furthermore, the best-fit number counts to the GOODS-S field using these different methods are consistent, and we find that our data is better described by a Schechter function model for the SMG number counts than a single power-law model. The depth and large survey area of the AzTEC/GOODS-S map have resulted in the tightest constraints to date on the SMG number counts at $S_{1.1 \text{mm}} = 0.5 \text{ mJy}$. Comparing our cumulative number counts to those from several SCUBA lensing cluster surveys at 850 $\mu$m, the lensing cluster number counts appear to be biased high assuming reasonable values for the flux-scaling from 850 $\mu$m to 1.1 mm. These results are consistent with those from large-area blank-field surveys at 850 $\mu$m with SCUBA, where the number counts at $S_{850 \mu m} \gtrsim 2 \text{ mJy}$ from lensing cluster surveys are systematically higher. We find that the number counts from the AzTEC/GOODS-S field are consistent with those from the 0.67 deg$^2$ AzTEC/SHADES survey.

From a stacking analysis on the AzTEC/GOODS-S map at the positions of BzK-selected galaxies in this field, we determine that the average SFR estimated from the 1.1 mm emission for star-forming BzKs identified as having a mid-IR excess is three times higher than the average SFR for normal star-forming BzKs. This result is confirmed by the SFRs estimated from the radio luminosity calculated from stacking the 1.4 GHz map at the position of the mid-IR excess and normal BzKs in GOODS-S. These results appear to be inconsistent with those of Daddi et al. (2007b) who claim that the SFRs of mid-IR excess BzKs are only $\approx 30\%$ higher than those of normal BzKs. However, it is possible that our stacking results are biased to the relatively rare sources where the amount of dust-extinction, and hence the SFR estimated from the
UV luminosity, has been significantly underestimated, leading to a misidentification of a mid-IR excess in these sources.

We resolve only 6 – 8% of the CIB at 1.1 mm into individual mm-bright galaxies. While the 24 µm population can account for the full energy density in the CIB at 250 – 500 µm, we estimate that 24 µm sources resolve only 21 – 28% of the CIB at 1.1 mm, demonstrating that a significant population of faint dust-obscured galaxies at $z \gtrsim 3$ that are largely missed at shorter wavelengths dominates the total energy density in the CIB at 1.1 mm.
CHAPTER 5

COMBINED 1.1 MM NUMBER COUNTS FROM AZTEC BLANK-FIELD SURVEYS

5.1 Introduction

Since the discovery of a significant population of high-redshift, dust-obscured galaxies detected at submillimeter (submm) and millimeter (mm) wavelengths (Smail et al., 1997; Hughes et al., 1998; Barger et al., 1998), understanding the role of these “submm/mm-galaxies” (or SMGs) in galaxy evolution has remained a key goal. Surveys at 850 $\mu$m with the Submillimeter Common User Bolometer Array (SCUBA) camera on the James Clerk Maxwell Telescope (JCMT) have revealed that SMGs were much more common in the past ($z \gtrsim 1$) than galaxies with comparable far-infrared (FIR) luminosities ($L_{\text{FIR}} \gtrsim 3 \times 10^{12} L_\odot$) observed in the local Universe (e.g. Borys et al., 2003; Scott et al., 2006; Coppin et al., 2006). Their projected number density is a factor of $\approx 1000$ greater than would be expected assuming no evolution in the local luminosity function (see for example Figure 1.5). SMGs appear to represent an important starburst phase in the assembly of massive galaxies, and their number counts can thus place important constraints on models of galaxy evolution (e.g. Granato et al., 2004; Baugh et al., 2005).

As discussed in Chapter 1, the only survey at 850 $\mu$m with sufficient area and depth to constrain the differential SMG number counts is the SCUBA Half Degree Extragalactic Survey (SHADES), which covers a total area of 0.25 deg$^2$ split equally between two separate regions of sky towards the Lockman Hole-East (LH-E) and the Subaru/XMM-Newton Deep Field (SXDF). When compared to other, smaller area
surveys at 850 µm, we see a large amount of variation in the number counts from field-to-field. This may be due entirely to statistical variations, or this may arise from true cosmic variance due to large-scale structure. We have not yet sampled a large enough area of sky at 850 µm to quantify the degree of cosmic variance, and it remains unclear whether the SHADES fields give an accurate estimate of the average number density of SMGs, or whether they represent a significant deviation from the blank-field average. Given the limited areas of the SCUBA/SHADES fields and the steep decline in the number counts with flux density, the number counts at $S_{850\mu m} > 15$ mJy are still poorly sampled. At the opposite end, the only (weak) constraints on the 850 µm number counts at $S_{850\mu m} < 2$ mJy come from SCUBA lensing cluster surveys, which use the natural magnification of background sources in the direction of intervening massive galaxy clusters to detect intrinsically less luminous sources. We have shown evidence that the number counts from such lensing cluster surveys are systematically biased high with respect to the number counts towards blank-fields (Section 4.5.3). Finally, we note that though deep, large-area surveys at 1.1 mm with Bolocam on the Caltech Submillimeter Observatory (CSO) and at 1.2 mm with MAMBO on the Institut de Radio Astronomie Millimetrique (IRAM) 30-m telescope have been carried out, the differential number counts from these surveys have not been published (Greve et al., 2004, 2008; Laurent et al., 2005; Bertoldi et al., 2007).

With the improved sensitivity and mapping speed of the AzTEC camera (Section 2.4) and nearly 2,000 hours devoted to SMG surveys with AzTEC on the JCMT and the Atacama Submillimeter Telescope Experiment (ASTE), we have imaged a total area of 1.74 deg$^2$ at 1.1 mm towards blank-fields to $1\sigma = 0.30 - 1.67$ mJy. In combining these data-sets, we can derive the most accurate blank-field number counts to date of submm/mm-selected galaxies. In this Chapter, we present the 1.1 mm number counts derived from combining the results from all blank-fields surveyed with AzTEC at the JCMT and ASTE. We summarize the surveys included in
this analysis in Section 5.2. In Section 5.3 we derive the number counts from the combined AzTEC blank-field data-sets. We conclude in Section 5.4 with a discussion of how we can use these results in the future to quantify the degree of field-to-field variations in the number counts, constrain models of galaxy evolution, and identify over-densities of SMGs in surveys towards biased environments.

5.2 Blank-field Surveys with AzTEC

A summary of the blank-field surveys carried out with AzTEC on the JCMT and ASTE, including the area, depth, and number of sources detected in each field, is presented in Table 5.1. These surveys include the AzTEC/JCMT surveys of the LH-E and SXDF, which collectively comprise the AzTEC/SHADES survey (Austermann et al., 2009a), and the Great Observatories Origins Deep-North (GOODS-N) field (Perera et al., 2008). On ASTE, we imaged the GOODS-S field (Chapter 4; Scott et al., 2009), two separate regions in the South Ecliptic Pole (SEP; Hatsukade et al., 2009) mapped in 2007 (SEP07) and 2008 (SEP08), and the AzTEC/ASTE survey of the COSMOS field (Wilson et al., 2009), which is the largest contiguous region ever mapped at 1.1 mm. In total, we have surveyed 1.74 deg$^2$ of sky to depths of $1\sigma = 0.30 - 1.67$. We do not include the AzTEC/JCMT survey of the COSMOS field (Chapter 3; Scott et al., 2008) in Table 5.1 nor in the number counts analysis in Section 5.3 since the same region is included within the larger ASTE survey of COSMOS and we wish to consider only independent data-sets in our calculations.

For each field, the area listed in Table 5.1 represents the “50% uniform coverage region”, where the pixel with the lowest amount of coverage in this region has half the weight as the pixel with the maximum coverage. We restrict the number counts analysis in Section 5.3 to the uniform coverage region in each field. The depths listed in Table 5.1 show the range in the root-mean-square (rms) noise level within the 50% uniform coverage regions. In total, we have detected 838 SMGs in blank-field surveys
Table 5.1. Summary of the blank-field 1.1 mm surveys taken with AzTEC on the JCMT and the ASTE. The columns give: 1) field name; 2) telescope used; 3) area of the field within the 50% uniform coverage region; 4) range of 1σ rms noise within the 50% coverage region; 5) number of “robust” source candidates as defined in Section 5.3; and 6) limiting $S/N$ ratio for the definition of robust source candidates as described in Section 5.3.

<table>
<thead>
<tr>
<th>Field</th>
<th>Telescope</th>
<th>Area (deg$^2$)</th>
<th>Depth (mJy/beam)</th>
<th>$N$</th>
<th>$(S/N)_{lim}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LH-E</td>
<td>JCMT</td>
<td>0.30</td>
<td>0.87 − 1.29</td>
<td>193</td>
<td>3.0</td>
</tr>
<tr>
<td>SXDF</td>
<td>JCMT</td>
<td>0.37</td>
<td>1.04 − 1.67</td>
<td>73</td>
<td>3.2</td>
</tr>
<tr>
<td>GOODS-N</td>
<td>JCMT</td>
<td>0.08</td>
<td>0.96 − 1.37</td>
<td>51</td>
<td>3.2</td>
</tr>
<tr>
<td>GOODS-S</td>
<td>ASTE</td>
<td>0.08</td>
<td>0.48 − 0.73</td>
<td>58</td>
<td>2.6</td>
</tr>
<tr>
<td>SEP07</td>
<td>ASTE</td>
<td>0.06</td>
<td>0.48 − 0.71</td>
<td>69</td>
<td>2.6</td>
</tr>
<tr>
<td>SEP08</td>
<td>ASTE</td>
<td>0.13</td>
<td>0.30 − 0.54</td>
<td>166</td>
<td>2.4</td>
</tr>
<tr>
<td>COSMOS</td>
<td>ASTE</td>
<td>0.72</td>
<td>1.04 − 1.51</td>
<td>228</td>
<td>3.2</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>1.74</td>
<td>0.30 − 1.67</td>
<td>838</td>
<td></td>
</tr>
</tbody>
</table>

from data-sets which we reduced using the same well-tested methods described in Section 3.3, making any study of the combined data-set straightforward.

### 5.3 Number Counts from the Combined AzTEC Blank-Field Surveys

We use the semi-Bayesian method described in Section 4.5.2 to calculate the 1.1 mm number counts from all AzTEC blank-fields listed in Table 5.1 combined. Since we have demonstrated that the number counts derived from this method are only weakly dependent on the assumed prior, we use the best-fit Schechter function model (Equation 4.3) to the AzTEC/SHADES number counts (Austermann et al., 2009a) with $(S', N_{3\text{mJy}}, \alpha) = (1.11 \text{ mJy}, 153 \text{ mJy}^{-1} \text{deg}^{-2}, -2)$ for the prior distribution. Since the prior flux distribution depends on the shape of the point source kernel, we calculate a separate prior for each of the fields. Similarly, we calculate the correction for survey incompleteness for each field separately, as this depends on the noise level in the map. Since several of our maps are very deep, we estimate the complete-
ness from fully simulated maps as described in Section 4.5.2 in order to include the effects of confusion noise. In previous number counts calculations using JCMT data (Perera et al., 2008; Austermann et al., 2009a,b), we only considered the effects of random noise for our completeness calculations, since confusion noise in these maps is negligible. However, as demonstrated in Section 4.4.5, we find that we must include the effects of confusion noise when calculating the survey completeness for most of our AzTEC surveys taken at the ASTE, where the beam full width at half maximum (FWHM) is larger (30″ versus 18″ on the ASTE and the JCMT, respectively) and the maps are generally deeper.

For each source candidate we determine its posterior flux distribution (PFD) as described in Section 3.5.1. We then sample the catalog of PFDs (with replacement) 20,000 times as described in Section 4.5.2, binning the sources by their flux densities in each iteration to estimate the differential and cumulative number counts. To select a “robust” list of sources (i.e. those which have a low probability of being a positive noise peak in the map), we limit our catalog to source candidates where the probability of deboosting to $< 0$ mJy is $\leq 20\%$ for sources detected in JCMT maps and $\leq 5\%$ for sources detected in ASTE maps. We choose different null thresholds for JCMT and ASTE data-sets based on comparisons between the Bayesian-estimated PFDs and PFDs from fully simulated maps. For the JCMT, we find that the fully simulated PFDs match the Bayesian-estimated PFDs within $\leq 1\%$ for $S_{1.1\text{mm}} \geq 0.5$ mJy for null thresholds $\leq 20\%$. The same is true for the PFDs of sources detected in ASTE maps for null thresholds $\leq 5\%$, where the difference likely arises from the larger beam size.

In the sixth column of Table 5.1, we list the limiting signal to noise ($S/N$) ratio for each field given our choice of null thresholds, and the fifth column gives the number of source candidates that meet this criterion. As noted in Section 4.5.2, the Bayesian method inherently corrects the number counts for false positives since we sample the
The differential and cumulative number counts from the combined AzTEC blank-fields are shown in Figure 5.1 and 5.2, respectively (black filled circles and 68.3% confidence error bars; for $S_{1.1\text{mm}} \leq 4.5$ mJy the error bars are smaller than the symbols). The number counts are listed in Table 5.2, and the covariance matrices for the differential and cumulative number counts are given in Tables 5.3 and 5.4, respectively. We fit the differential number counts to a Schecther function model given by Equation 4.3, fixing $\alpha = -2$; the best-fit model and 68.3% confidence region is shown in Figure 5.1 by the solid black curve and gray shaded region, respectively. Given the tight constraints on the number counts, we also fit the data to the same model with $\alpha$ as a free parameter and find that the results are consistent, with the best-fit $\alpha = -2.06^{+0.20}_{-0.15}$. Given the large dynamic range in flux densities probed by the combined AzTEC blank-fields, we can conclusively rule out a single power-law model for the number counts. We list the best-fit parameters for these models in Table 5.5. From the $\chi^2$ metric calculated using Equation 4.5 (last column in Table 5.5), the Schechter function model clearly provides a better description of the 1.1 mm number counts.

We use a bin-size of 1 mJy in order to obtain strong constraints on the number counts. We calculate the number counts using two different values for the minimum flux density – 1.0 mJy and 0.5 mJy – in order to test for systematics in the Bayesian method. For a minimum flux density of 1.0 mJy, we have fully tested the Bayesian method on both JCMT and ASTE data and confirmed that there are no strong biases in the results, so we are confident that our number counts are accurate down to 1.0 mJy. At 0.5 mJy, we have demonstrated in Section 4.5.2 that the Bayesian method is largely free of systematics for surveys with $1\sigma \approx 0.5$ mJy; however, we have yet to verify that the number counts at 0.5 mJy can be determined from shallower
Figure 5.1. The 1.1 mm differential number counts (black filled circles) for the combined AzTEC blank-field surveys on the JCMT and the ASTE. The error bars represent the 68.3% confidence intervals. The solid black curve and shaded gray region indicate the best-fit Schechter function and 68.3% confidence interval (row 1 of Table 5.5). For comparison, the number counts determined from each of the individual fields listed in Table 5.1 are shown as labeled on the Figure. The black horizontal dashed line in the bottom-right corner indicates the survey limit for the combined blank-fields, where the number counts will Poisson deviate to 0 mJy$^{-1}$deg$^{-2}$ 31.7% of the time. The survey limits for each of the individual blank-fields are also shown (color-coded to match the corresponding data-points for the same field). The green dot-dashed curve, purple dotted curve, and cyan and blue dashed curves show the predicted 1.1 mm number counts from the galaxy evolution models of Granato et al. (2004), Baugh et al. (2005), and Rowan-Robinson (2009), respectively.
Figure 5.2. The 1.1 mm cumulative number counts for the combined AzTEC blank-field surveys on the JCMT and the ASTE. All symbols are the same as those in Figure 5.1. The shaded black region indicates the 68.3% confidence interval on the cumulative number counts of very bright sources determined from the 100 deg$^2$ survey from the SPT (Vieira et al., 2009). The flux densities for the SPT number counts have been scaled to 1.1 mm assuming a flux ratio of $S_{1.1\text{mm}}/S_{1.3\text{mm}} = 1.6$. 
Table 5.2. The 1.1 mm differential and cumulative number counts for the combined AzTEC blank-field surveys. The errors indicate 68.3% confidence intervals.

<table>
<thead>
<tr>
<th>Flux Density (mJy)</th>
<th>dN/dS (mJy$^{-1}$deg$^{-2}$)</th>
<th>Flux Density (mJy)</th>
<th>N(&gt; S) (deg$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.84</td>
<td>3290. $^{+220.}_{-230.}$</td>
<td>0.50</td>
<td>4250. $^{+230.}_{-230.}$</td>
</tr>
<tr>
<td>1.88</td>
<td>631. $^{+42.}_{-43.}$</td>
<td>1.50</td>
<td>958. $^{+46.}_{-48.}$</td>
</tr>
<tr>
<td>2.90</td>
<td>208. $^{+16.}_{-17.}$</td>
<td>2.50</td>
<td>327. $^{+20.}_{-20.}$</td>
</tr>
<tr>
<td>3.91</td>
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<td>119.5 $^{+8.7}_{-9.8}$</td>
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<td>4.91</td>
<td>27.1 $^{+4.0}_{-4.6}$</td>
<td>4.50</td>
<td>45.6 $^{+5.4}_{-5.4}$</td>
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<td>5.91</td>
<td>9.9 $^{+2.3}_{-2.6}$</td>
<td>5.50</td>
<td>18.5 $^{+3.0}_{-2.8}$</td>
</tr>
<tr>
<td>6.91</td>
<td>4.1 $^{+1.3}_{-1.8}$</td>
<td>6.50</td>
<td>8.6 $^{+1.9}_{-1.9}$</td>
</tr>
<tr>
<td>7.92</td>
<td>1.9 $^{+0.8}_{-1.2}$</td>
<td>7.50</td>
<td>4.5 $^{+1.5}_{-1.4}$</td>
</tr>
<tr>
<td>8.92</td>
<td>1.1 $^{+0.5}_{-0.9}$</td>
<td>8.50</td>
<td>2.6 $^{+1.1}_{-1.8}$</td>
</tr>
<tr>
<td>9.92</td>
<td>0.7 $^{+0.4}_{-0.7}$</td>
<td>9.50</td>
<td>1.5 $^{+0.1}_{-1.0}$</td>
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</table>

Table 5.3. The covariance matrix for the differential number counts for the combined AzTEC blank-field surveys. The units are in mJy$^{-2}$deg$^{-4}$.

<table>
<thead>
<tr>
<th>Flux Density (mJy)</th>
<th>0.84</th>
<th>1.88</th>
<th>2.90</th>
<th>3.91</th>
<th>4.91</th>
<th>5.91</th>
<th>6.91</th>
<th>7.92</th>
<th>8.92</th>
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</thead>
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<td>51500.</td>
<td>6110.</td>
<td>1130.</td>
<td>280.</td>
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<td>2.3</td>
<td>0.6</td>
<td>-1.2</td>
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<td>1800.</td>
<td>455.</td>
<td>108.</td>
<td>23.7</td>
<td>4.1</td>
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<td>-0.3</td>
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</tbody>
</table>
Table 5.4. The covariance matrix for the cumulative number counts for the combined AzTEC blank-field surveys. The units are in deg$^{-4}$.

<table>
<thead>
<tr>
<th>Flux Density (mJy)</th>
<th>0.50</th>
<th>1.50</th>
<th>2.50</th>
<th>3.50</th>
<th>4.50</th>
<th>5.50</th>
<th>6.50</th>
<th>7.50</th>
<th>8.50</th>
<th>9.50</th>
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</thead>
<tbody>
<tr>
<td>0.50</td>
<td>53700</td>
<td>2170.</td>
<td>350.</td>
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<tr>
<td>1.50</td>
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<td>370.</td>
<td>93.0</td>
<td>29.3</td>
<td>11.3</td>
<td>4.5</td>
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<td>361.</td>
<td>89.9</td>
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<td>0.7</td>
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<tr>
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<tr>
<td>9.50</td>
<td>0.8</td>
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</table>

Table 5.5. Parameters for the best-fit models to the differential number counts derived from the combined blank-field surveys with AzTEC. The errors on the best-fit parameters represent marginalized 68.3% confidence intervals. When an error is not listed, the parameter is fixed to the given value. The last column shows the $\chi^2$ metric for the fit calculated using Equation 4.5.

<table>
<thead>
<tr>
<th>Model</th>
<th>$S'$ (mJy)</th>
<th>$N_{3\text{mJy}}$ (mJy$^{-1}$deg$^{-2}$)</th>
<th>$\alpha$</th>
<th>$\chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eqn 4.3</td>
<td>$1.34_{-0.06}^{+0.03}$</td>
<td>$180._{-9}^{+6}$</td>
<td>$-2.0$</td>
<td>3.46</td>
</tr>
<tr>
<td>Eqn 4.3</td>
<td>$1.32_{-0.10}^{+0.20}$</td>
<td>$181._{-10}^{+5}$</td>
<td>$-2.06_{-0.15}^{+0.20}$</td>
<td>4.52</td>
</tr>
<tr>
<td>Eqn 4.4</td>
<td>$- -$</td>
<td>$88._{-6}^{+9}$</td>
<td>$-4.01_{-0.03}^{+0.09}$</td>
<td>148.</td>
</tr>
</tbody>
</table>
surveys with $1\sigma \approx 1.0$ mJy using this method, as in these cases the completeness estimate is quiet low (a few percent) and the PFDs may be poorly estimated at such faint flux levels. However, we find that we are able to determine the same best-fit parameters to the Schechter function model for both sets of the number counts, and we see no other signs of strong biases in the Bayesian-extracted number counts at 0.5 mJy.

5.4 Summary and Future Work

The total survey area and depths of the AzTEC blank-field projects have resulted in the strongest constraints on the average number counts of submm/mm-selected galaxies over a large dynamic range in brightness from $0.5 < S_{1.1\text{mm}} < 10$ mJy. Comparing the number counts from each of the individual AzTEC blank-fields (data-points shown in Figures 5.1 and 5.2), we see some amount of field-to-field variations, with some fields (like GOODS-N and SEP07) being slightly over-dense and others (like SXDF) being slightly under-dense. We can now begin to quantify the degree of cosmic variance observed and address whether it is consistent with expectations given the distribution of large-scale structure in the Universe. The large contiguous areas mapped by AzTEC, in particular the $0.72 \text{deg}^2$ ASTE/COSMOS field, will also enable us to measure the clustering properties of SMGs and to test the hypothesis that these sources trace the highest density peaks in the dark matter distribution and are associated with the formation of massive spheroidal galaxies.

The number counts from the combined AzTEC blank-fields also provide important information for constraining models of galaxy evolution. For example, we show the 1.1 mm number counts predicted from a few galaxy evolution models (Granato et al., 2004; Baugh et al., 2005; Rowan-Robinson, 2009) in Figures 5.1 and 5.2. These models are able to reproduce the $850 \mu \text{m}$ number counts from previous SCUBA surveys (Silva et al., 2005; Lacey et al., 2008; Swinbank et al., 2008). While a couple of these models
marginally agree with our 1.1 mm differential number counts at $S_{1.1\text{mm}} \lesssim 5 \text{ mJy}$, all of them over-predict the number counts at $S_{1.1\text{mm}} \gtrsim 6 \text{ mJy}$. The number counts from our combined AzTEC data-sets thus require refinements in these models of galaxy evolution. We caution however that weak lensing from tenuous, low-redshift foreground structure may biases the SMG number counts high, as we found evidence for in the AzTEC/COSMOS survey taken on the JCMT (Section 3.8). Using the galaxy density map of Scoville et al. (2007a) and the 0.72 deg$^2$ COSMOS survey with AzTEC on the ASTE – which includes regions of low galaxy density – we can repeat our analysis in Section 3.8 to better access the influence of foreground structure on the SMG number counts.

We can also compare our results with the number counts of very bright point sources detected at 1.3 mm in the 100 deg$^2$ survey with the South Pole Telescope (SPT; Carlstrom et al., 2009), which are represented by the shaded black region in Figure 5.2 (Vieira et al., 2009). The flux densities for these number counts have been scaled to 1.1 mm assuming a flux ratio of $S_{1.1\text{mm}}/S_{1.3\text{mm}} = 1.6$. The exponential falloff at the bright-end predicted by extending our best-fit Schechter function beyond the survey limit is clearly inconsistent with the SPT results. This turnoff at $S_{1.1\text{mm}} \approx 15 \text{ mJy}$ is similar to that seen in predictions from the galaxy evolution model of Baugh et al. (2005), where the $S_{1.1\text{mm}} \gtrsim 15 \text{ mJy}$ number counts are dominated by low-redshift quiescent galaxies. However, it is possible that the behavior of the bright-end number counts arises from a significant population of flat-spectrum radio-loud active galactic nuclei (AGN), or alternatively, from lensed galaxies at high-redshift as proposed by Lima et al. (2009) to explain a similar turnoff observed in the 500 $\mu$m number counts determined from surveys with the Balloon-borne Large Aperture Submillimeter Telescope (BLAST). The bright-end number counts measured by Vieira et al. (2009) combined with the SMG number counts from our AzTEC blank-field surveys thus present new challenges for models of galaxy evolution.
The strong constraints on the 1.1 mm blank-field number counts are also crucial for characterizing the SMG populations observed towards regions of known over-densities. During the 2007 and 2008 observing seasons on ASTE, we imaged 40 separate 100 arcmin$^2$ fields centered on known clusters and proto-clusters from $0 < z < 4$ for the AzTEC/ASTE Cluster Environment Survey (ACES), with the goal of understanding how the evolution of massive starburst galaxies within clusters differs from that in unbiased environments, and how this changes as a function of redshift. The number counts from the combined AzTEC blank-field surveys will serve as a baseline for quantifying possible over-densities observed in these biased regions.
CHAPTER 6

CONCLUSIONS

Deep, large-area extragalactic surveys using the new millimeter- (mm-) wavelength camera AzTEC on the James Clerk Maxwell Telescope and the Atacama Submillimeter Telescope Experiment will lead to significant advancements in our understanding of the evolution of massive starburst galaxies in the early Universe. Over the past four years, we have imaged three times the area in blank-field surveys mapped by previous submm/mm instruments. Since all of the fields imaged with AzTEC have been reduced and analyzed using the same well-tested methods, we have been able to combine the surveys from disjoint regions in order to calculate the most accurate measurement of the 1.1 mm blank-field number counts to date, which provides important constraints for models of galaxy evolution. This uniform data-set will also allow us to quantify the degree of cosmic variance observed in the 1.1 mm number counts due to large-scale structure, and the large area mapped with AzTEC will enable us to measure the clustering properties of mm-selected galaxies. In addition to these blank-field extragalactic surveys, we have imaged the extended environments of 40 galaxy clusters and proto-clusters over a range in redshifts in order to study the effects of environment on the evolution of massive galaxies.

These extragalactic surveys carried out with AzTEC have resulted in the detections of \( \sim 1000 \) previously unknown mm-galaxies located within some of the most widely studied fields, many with deep imaging at radio, mid-infrared, optical, and X-ray wavelengths. Much of this complementary data is readily available, and we have already begun the process of multi-wavelength counterpart identification for several
of our data-sets in order to better understand the nature of these sources. These sur-
veys provide a homogeneous sample of bright mm-galaxies which we plan to target for
some of the first observations with the redshift search receiver on the Large Millimeter
Telescope when this facility is commissioned in late 2009. The mm-galaxies detected
with AzTEC will also be interesting targets for high-resolution imaging with the At-
acama Large Millimeter Array, which will enable the first studies of the distribution
of dust within these high-redshift massive galaxies.
BIBLIOGRAPHY


Austermann J. E., et al., 2009a, ArXiv e-prints


Blain A. W., Smail I., Ivison R. J., Kneib J.-P., Frayer D. T., 2002, Physics Reports, 369, 111


Carlstrom J. E., et al., 2009, ArXiv e-prints


160
de Vaucouleurs G., 1959, Handbuch der Physik, 53, 275
Ferrusca D., et al., 2009, in preparation
Griffin M. J., Orton G. S., 1993, Icarus, 105, 537
Hatsukade B., et al., 2009, in preparation
Johnson S. P., et al., 2009, in preparation
Marsden G., et al., 2009, ArXiv e-prints
Mather J. C., 1984, Applied Optics, 23, 584


Roberts M. S., 1963, ARA&A, 1, 149


Scott K. S., et al., 2009, in preparation
Sunyaev R. A., Zeldovich Y. B., 1972, Comments on Astrophysics and Space Physics, 4, 173

167
van den Bergh S., 1975, ARA&A, 13, 217
Wilson G. W., et al., 2009, in preparation