Over Fences and Into Yards: Privacy Threats and Concerns of Commercial Satellites

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ABSTRACT

Commercial satellite imaging is used for diverse applications in a wide range of sectors, from agriculture to the military. As satellite images continue to become more widely available and detailed in resolution, the potential for individual and population-level monitoring increases and raises new privacy concerns compared to previous Earth observation technologies. We anticipate that these technologies will only continue to improve in the upcoming decade. To better understand privacy threats and concerns of commercial satellite imagery, we conducted a survey of 99 participants from the United States. We found that most respondents were not aware that commercial satellites existed, and once informed about the capabilities of commercial satellites, most are not comfortable with how good the current state-of-the-art satellite imaging capabilities are. Few respondents want satellite imagery cost-free and widely available, which conflicts with current trends in geospatial data. In addition to aiding our understanding of the public's current perception and relationship with remote sensing technologies, we use these results to propose possible new satellite image legislation, regulation, and technological mitigations, both nationally and internationally.

KEYWORDS

satellites, privacy, survey, remote sensing

1 INTRODUCTION

Space exploration in the 20th century opened the ability to observe and measure Earth from a completely new perspective. While offering numerous benefits, this vantage above the planet also creates new potential avenues of human surveillance, including satellite imagery, which can surveil the Earth's entire surface. As satellite imagery resolution continues to improve, its providers have also expanded access to these images beyond just governments. Since the 1990s, many governments, including the United States, have permitted commercial satellite companies to sell imagery to both governmental and non-governmental customers.

Commercial satellite companies collect images from satellites and sell these images to customers, and can even sell to individual people. These customers use the images for a variety of applications, including agriculture, scientific research, identifying illegal activity (e.g., cannabis farming and illegal, unreported, and unregulated (IUU) fishing), defense, and even finance [50]. International and U.S. space law embody a web of complex legislation [40] that is continuously evolving [63], but U.S.-based restrictions on spatial resolution of imaging devices have relaxed in recent years.

Compared to platforms like Google Earth and Google Maps, which purchase and sometimes post-process commercial satellite and aerial imagery, direct-to-consumer commercial satellite imagery introduces unique privacy and security challenges. In addition to being able to purchase unaltered images on-demand directly from a commercial satellite company, another key difference is the temporal resolution of commercial satellite companies, or the frequency at which they image: whereas Google Earth provides undated high-resolution images that are not frequently updated, commercial firms collect imagery of any given location of Earth up to multiple times a day, sometimes dependent on customer requests [46, 47]. This high temporal resolution can allow individuals to be tracked across time at a higher granularity. Abstractly, drones might represent a similar technology to satellite imagery in that they can capture bird's eye view images any time each day. If someone flies a drone, they may likewise have access to raw, unedited images of the Earth. But unlike satellites, most drones in the commercial market are detectable through at least sight, potentially alerting those who can see the drones of their presence and thus temporarily affecting how they behave while a drone is nearby (discussed further in Section 2).

Our work is motivated by the observation that (1) commercial satellite image resolution continues to improve in spatial, temporal, and spectral resolution (the minimum portion of the electromagnetic spectrum that it can resolve), (2) these images are simultaneously becoming cheaper and more widely available, which has important implications to individual privacy, and (3) satellite images might *not* be post-processed from a privacy-protecting and anti-surveillance perspective. Our research is the result of a cross-disciplinary collaboration spanning computer security and privacy (two authors), social psychology (one author), and political geography with a focus on remote sensing (one author). We aim to understand what current and future individual privacy threats commercial satellites pose, so that we can better consider possible mitigations to these privacy risks. It is important to understand the risks before commercial satellite capabilities improve further.

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To guide our study and analyses, we formulated two research questions. Our first research question is:

- RQ1: What factors influence privacy versus utility considerations of satellite imagery?

As noted earlier, there are numerous commercial satellite imagery use cases that offer significant positive benefits. However, there are also privacy risks. RQ1 is designed to help understand how people consider and weigh privacy versus utility, and what those tensions between privacy and utility are. Foreshadowing our results, and as we hypothesized at the outset of this project, we find privacy and utility to be in tension both within individual respondents' reasoning and between respondents. Given the significant investment in commercial satellite imagery, we believe that it is inevitable that commercial satellite imagery will continue to decrease in cost and increase in spatial and temporal resolution. Thus, absent significant forethought, the risks to people of privacy invasion and surveillance may heighten. Ultimately, our goal is not simply to acknowledge that tensions exist between privacy and utility, and that the risks of privacy and surveillance harms may increase in the future, but to provide guidance on how to navigate those tensions. With this in mind, and informed by our findings with respect to RQ1, we formulate our second research question below:

- RQ2: What possible regulatory, legislative, and technological approaches are there to protect individual privacy against commercial satellite imagery, and how do those approaches address the factors and tensions identified in RQ1?

To answer our research questions, we conducted a survey of 99 U.S. residents. We focus on respondents in the U.S. so that we can understand possible U.S.-specific legislation recommendations, though many of these could extend internationally, particularly as many technological standards set in the U.S. end up being adopted in other national and international contexts. The U.S. has also already demonstrated initiative in setting pioneering regulations to govern satellites, as with its commitment to not perform direct-ascent-anti-satellite missile testing [29] promulgated in 2021.

Our survey responses directly inform our analysis of RQ1. Elements of our survey also contribute directly to our answer to RQ2, though we reach beyond just our survey's responses as we answer RQ2. Namely, our answer to RQ2 is a result of the synthesis of our survey's answers, additional reflection, and the perspectives brought by our diverse backgrounds (political geography, psychology, and computer security and privacy). We pose key considerations for legislators and regulators, as well as possible technological protections to individual privacy (Section 7). By raising awareness among researchers and practitioners, we hope that future research and communication with the public will help inform future decisions in how to manage commercial remote sensing technologies as they proliferate worldwide.

2 BACKGROUND AND RELATED WORK

Spatial and Temporal Resolution. Spatial resolution is the smallest dimension on the Earth's surface represented by one pixel in an image, e.g., a 3m spatial resolution means that one pixel in the captured satellite image represents a 3 x 3m square of the Earth's surface. Temporal resolution is the frequency at which images are taken. A 1 day temporal resolution means satellite images are taken of a particular location on Earth up to once per day.

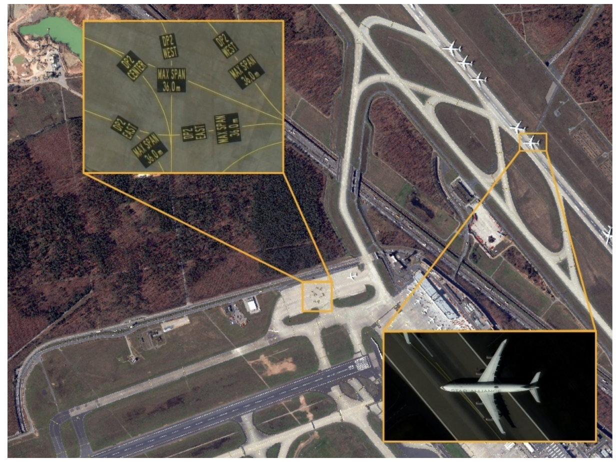

Figure 1: Example of 15cm resolution satellite image from Maxar [23]

Satellite Capabilities. Commercial Earth observation satellites have been on the market since the late 1980s [60], and are now offered by a variety of companies. Commercial satellites' spatial resolution has drastically improved from tens of meters to now centimeters, with some commercial satellite companies boasting resolutions of 15cm [23], shown in Figure 1. Public documents suggest that U.S. government military satellites may offer 10cm resolution or better [43]. Thus, there is potential for commercial satellite companies to offer higher resolution in the future. Some satellite imagery provides both high spatial and temporal resolution; satellite "videos" stitch discrete satellite images into videos that last between 30 seconds and two minutes [51]. Although not available yet, startup EarthNow aims to create a real-time video stream of the whole Earth [4, 8]. For satellites taking more than a short video clip, temporal frequency capabilities are lower, but are still high at up to 15 times per day [38].

In addition to visible wavelengths, satellite imagery captures other spectral bands. For example, healthy vegetation reflects near infrared wavelengths, which can be measured to help determine crop health and deforestation [49]. There are also different forms of radar, including Synthetic Aperture Radar (SAR). SAR imaging allows for observation at night and cloud cover penetration [22], making it highly useful in military and surveillance contexts.

While many satellite images are taken at an angle perpendicular to the ground, some are also capable of imaging many degrees off this angle, known as "off-nadir". We include a real example in Figure 2 to demonstrate the capabilities of this type of spaceborne imaging. As a first work to study privacy and utility tensions with commercial satellite imagery, we focus on today's most common commercial satellite image form: perpendicular to the Earth.

Related Technologies. Prior work has raised privacy concerns in related technologies that can measure images from a bird's eye view, including drones, Google Earth and Google Street View. Google

Figure 2: Example of a 60° off-nadir satellite image from Planet Labs [33]

Earth provides the public with free, undated, high-resolution overhead images of most locations on Earth. Google Earth Pro, with its timeslider function, offers more historical satellite imagery, yet it still is typically only available at time intervals of one year apart or longer and thus is less of an individual privacy threat than purchasing commercial satellite images at a high temporal resolution.

In the U.S, there are concerns that Google Earth and other similar services violate reasonable expectations of privacy [36]. In France, the French government used Google Earth data and artificial intelligence to detect undeclared pools that were circumventing French tax laws in residents' backyards in 2022 [13]. To foreshadow our findings in Section 6.4, many people were uncomfortable with imaging backyards, even to capture illegal activity. Although these practices may become more commonplace, some may see them as an invasion of privacy, which will be important for regulators, legislators, and commercial satellite providers to consider.

Multiple works explore how users view drones as a privacy concern [14, 65]. Concerns such as drones recording without consent [14] and stalking [65] also apply to potential surveillance through commercial satellites. Drones are similar to satellites in that they can take high-resolution bird's eye images. From the perspective of an adversary, using drones and satellites to violate individual privacy have different tradeoffs. Drones require a one-time purchase and will cost less money upon taking multiple images compared to current satellite imagery prices. Most drones would be detectable while in the air, at least visually, and thus the adversary would risk exposing their presence. With satellites, most people are not aware of when one is taking images over their area. Satellite images are currently lower resolution than drones but with time, the difference between their spatial resolutions may decrease. Further, whereas a purchaser of a commercial satellite image does not need to be physically near the surveilled location, the pilot of a drone (or at least the drone itself) must be physically in the same vicinity.

In Google Street View, there have been privacy concerns and efforts to blur out humans, license plates, and other personal information [21, 24, 41]. Google allows people to request to blur their face or home in Google Street view [27]. It is unclear what satellite companies blur and how it differs by company. Even still, the update frequency of Street View images is lower than the temporal resolution capabilities of commercial satellites.

Commercial Satellites Security and Privacy. Privacy concerns surrounding commercial satellite imagery have existed for decades and remain a topic of concern [8, 45, 52, 60]. Atluri et al. construct an authorization model for those using satellite data, which provides different spatial resolutions for different authorization levels [6]. Black discusses privacy concerns of commercial satellite imagery [11], though the focus is more on protecting privacy of U.S. military efforts and protecting national security than individual privacy. Concrete examples of satellites in use have affected other countries' privacy and have benefited the U.S.: an off-nadir photo was used to discover a North Korean submarine docked in North Korea that was hidden from perpendicular angle photos by an awning [57]. To our knowledge, no previous research has deeply investigated individual privacy concerns for commercial satellite imagery; our work fills this gap.

Democratization of Access to Satellite Imagery. There are movements in industry and the geography field overall to democratize access to imagery, i.e., to make satellite images more widely available and lower cost (and even no-cost). Skyfi, a startup whose app launched in early 2023 [67], states that its mission is to "democratize satellite film and imaging. What was once a high-tech process is now simple, affordable and accessible to everyone." [58].

Many geographers support democratization efforts, such as aiding in armed conflicts [9] and scientific research [66]. The Consortium for Execution of Rendezvous and Servicing Operations (CONFERS) [17] recommends that "the U.S. government should declare the space domain as a public space and the ability to conduct [imaging from space] as the equivalent of taking photos of public activities on a public street" [16].

Satellite Regulation/Legislation. Laws surrounding remote sensing are complex, and have even been described as "byzantine" [40]. They also have changed dramatically over the past several decades. While the U.S. government previously limited spatial resolution of U.S.-based commercial satellite companies to only have as good of spatial resolution as the best resolution of foreign competitors [54], the Licensing of Private Remote Sensing Space Systems rule of 2020 removed this restriction [44]. Then, in 2023, in a move to ensure the U.S. commercial satellite sector's continued international dominance, the National Oceanic and Atmospheric Administration's Commercial Remote Sensing Regulatory Affairs office ended temporary restrictions which had limited rapid revisit over certain areas. The regulatory change also enables imaging and distribution for 99% of the Earth's surface and removes previous limitations on X-Band Synthetic Aperture Radar capabilities [32]. There is also an ever-growing number of foreign commercial satellite companies that are not governed by U.S. restrictions, such as China's GaoFen satellites and France's SPOT Images [3] (with a previous spot satellite sold in 2014 to Azerbaijan [19]), to name just a few.

3 PRE-SURVEY METHODOLOGY

Before creating our survey on people's threat perceptions and concerns, we took the following steps:

(1) Conducted a brainstorming exercise among security and privacy experts and non-experts to generate a set of privacy concerns of satellite imagery (Section 3.1);

(2) Purchased real satellite images to better understand the current state of commercial satellite imagery processes (Section 3.2).

3.1 Brainstorming Exercise

We conducted a collaborative brainstorming exercise among 25 colleagues to explore the space of potential privacy threats and concerns of commercial satellite imagery. Our goal in understanding these threats was to inform the questions we constructed in our survey. We developed two separate codebooks based on these brainstorming sessions:

(1) A private activity image metric codebook: aspects of images that if observed, could violate individual privacy (discussed in Section 3.1.2);
(2) A privacy threats and concerns codebook: a summary of themes that emerged of types of activities that might violate privacy if imaged (discussed in Section 3.1.2).

3.1.1 Brainstorming Exercise Methodology. We discussed privacy concerns of commercial satellite imagery across multiple sessions where half of the volunteer colleagues were security and privacy experts; the other half were outside of the security and privacy field, including a geographer. This methodology was inspired by Hiniker et al [28]; we complement this expert panel with colleagues outside of security and privacy to offset possible biases within the security and privacy field. Our sessions took the form of individual brainstorming and writing of ideas, a group discussion to surface potentially even more ideas, or both in that order during the same brainstorming session. For all of our brainstorming sessions, we used the following two prompts: "What activities might someone do near their home that they do not want captured with satellite images? Please list as many as possible, including activities that you don't do but someone else might", and the second prompt was the same except it asked about activities *away from* someone's home. Lastly, one author went through a structured brainstorming threat modeling exercise based on brainstorming cards from Denning et. al [20], and then discussed these results with a second author, who is an expert in security and privacy.

While the pre-study activities were not the focus of our research, we sought to maximize the potential of pre-study activities to positively influence the content and format of our actual study (Section 4). Thus, we adopted qualitative study best practices as we analyzed our pre-study data. Through notes and written responses collected from these brainstorming sessions, one author developed two initial codebooks and performed thematic analysis [12] of all ideas that were surfaced in the brainstorming sessions. The main coder updated and discussed with a second author throughout the process of coding, and also met once to discuss all notes collected during the process, as well as discussing coding and theme construction. We used this process for both codebooks.

3.1.2 Brainstorming Exercise Analysis. Both codebooks that we produce through our analysis are meant to be a guide for our study and not a generalizable taxonomy.

Privacy Threats and Concerns Codebook. We constructed an activities type codebook to generate content for a subset of questions in the user study. For this codebook, we coded for types of private activities that could potentially be captured by satellite imagery. From our brainstorming notes, we categorized everything into the following three activity types:

(1) "Innocuous": activities that we believe many United States residents deem culturally acceptable and legal. Brainstorming session examples include going to a bank and shopping.
(2) "Doxxing/Non-universal acceptance": activities which are legal in the United States, but might not be widely accepted in United States society. These include visiting sensitive locations such as a mental health clinic or going somewhere instead of work when claiming to be sick.
(3) "Illegal": any activity that is illegal in at least some part of the United States, such as speeding or growing marijuana.

Private Activity Image Metric Codebook. We used the private activity image metric codebook to map private activities to aspects of images that would need to be observable in order to see that private activity. The metrics were based on the privacy concerns people brought up in the brainstorming session. The full codebook diagram is included in Appendix C for reference. An example metric is being able to observe "people body position", from which someone can infer whether someone is doing a particular activity, such as running. Another example metric is "which car" which could be used to distinguish between cars and track someone's car location across time. We use this codebook to help construct some of our survey questions, such as asking about choosing between two scenarios that require being able to observe the same type of image metric, or metrics that require around the same spatial resolution to observe.

3.2 Ordering Commercial Satellite Images

To understand what the commercial satellite image purchasing process is like for civilians, we shopped for images from three U.S.-based vendors, which we anonymize as *A*, *B* and *C*, and one Chinese vendor, *D*. Vendor *C* was the least expensive and the easiest to purchase, so we only purchased from them. Purchasing on-demand 75cm spatial resolution images over our institution's campus from Vendor *C* cost around $175 each time. Vendor *C* did not require any human interaction. We ordered an image twice, and each time we received our photos within a couple days of requesting them. This simple process contrasts with two older companies, *A* and *B*, that we inquired. Company *A* offered a sales option of $15,000, and company *B* required a minimum purchase of $5000. Company *A* required filling out a form. They never responded to one author but did respond when another author requested photos separately. Company *D* offered on-demand 30cm spatial resolution imagery for a minimum of $5600, but the company was based in China and it was only possible to pay via WeChat; the complexity of getting permission to purchase from company *D* precluded us from proceeding. We expect that the trend of decreasing price and increasing ease of purchase of satellite images will continue, which also increases the possibility for people to potentially misuse these purchases.

4 SURVEY METHODOLOGY

We developed a study to answer our underlying research questions RQ1 and RQ2. The entire survey is included in Appendix A for reference. Through this survey, we sought to understand respondents' awareness, privacy perceptions, and privacy concerns surrounding commercial satellite imagery, as well as their perspectives on balancing privacy with utility. We conducted a pilot study of 15 participants. We read through and studied every response. Because we thought the participants were interpreting the questions how we expected, we did not adjust any of the survey structure following the pilot study.

4.1 Participants

We recruited participants from Amazon Mechanical Turk. We recruited them from only the United States because we wanted to understand how United States residents' responses and concerns compared to current United States commercial satellite regulation. To increase the likelihood of high-quality responses, we filtered for an Mturk approval rating of over 98% and an Mturk Masters Qualification. Through an a priori power analysis for a one-sample t-test using G*Power, we determined that 90 participants were needed to detect a small-moderate effect size (d = 0.30) at 80% power with a criterion of $\alpha = .05$. We oversampled to allow for possible exclusions based on inattention or falsely entering a code on MTurk. Our final results consisted of 99 complete survey responses. They were compensated $5 for an estimated survey time of 20 minutes. On average, participants took around 30 minutes to complete the survey. Other demographic details are included in Table 1.

4.2 Survey Structure

MTurk workers were told that we wanted to understand their thoughts about satellites. We purposely avoided discussion on privacy or harms to avoid priming them to think negatively about satellites. Participants first read the consent form including a description of the study. We then provided definitions of satellite-view imagery and filtered for understanding of these definitions by asking them to label three images as a "satellite view" image or not a "satellite view" image. Secondly, we filtered for visual impairment since some questions involve evaluating images. After filtering, there were 99 respondents.

Awareness and Initial Perceptions. Participants read a brief description of how commercial satellites are used today. To assess overall awareness, we asked whether people have heard about commercial satellites based on that definition. Next, to begin to evaluate how people weigh privacy risks versus utility, participants responded to two open-ended questions evaluating (1) what they think are the possible benefits of satellite images, and (2) what they think are the possible harms of satellite images. These questions came first in the survey to promote creativity in responses and to avoid priming with specific scenarios of privacy violations. We asked several other questions assessing awareness of satellite image practices, including what they thought the current spatial resolution, temporal resolution, and cost of satellite imagery is. For spatial resolution, we showed drone images that we took at different spatial resolutions, ranging from 15cm (the highest commercial satellite resolution today) to 10m resolution (see Ethics Section 5 for our drone imaging practices).

Weighing benefits and privacy harms. To help evaluate how people weigh personal privacy compared to the benefits satellite imagery could bring, we asked participants to consider possible pairs of scenarios. Participants could choose to allow either both scenarios or neither scenario, but not one or the other. This "would you rather" question formulation was inspired in part by the methodology from Simko et al. [56]. We chose to allow only "both" or "neither" responses to the scenario pair questions to require participants to choose whether they value privacy or utility more for the given scenario pair. We constructed scenarios based on the image privacy metric codebook, as discussed in Section 3 and presented in more detail in Appendix C. For each question, we paired a scenario with clear benefits and a scenario with privacy implications that both require a similar spatial resolution in order to be detected. For example, the first question contained two scenarios where the car presence metric is observed: one where a satellite would detect the existence of cars in hospital parking lots to estimate disease levels over time (beneficial), and one where an employer takes an image over their employee's home to ensure their car is there after the employee called in sick (privacy implications). To understand the factors involved in why people chose to allow both or neither scenario, we also asked them to explain each answer in a free response box. Table 2 presents each scenario pair, along with the results, which we return to in Section 6.3.

Comfort. We asked additional questions to understand the factors that might influence people's consideration of privacy and utility. We gave participants examples of locations satellites might image, activities that satellites might image, and entities who might have access to satellite imagery. The majority of our examples were inspired by the concerns people brought up in the brainstorming session (Section 3.1). Participants were asked to sort each activity and location into whether they thought it was acceptable or unacceptable to be imaged by satellites. For entities, they were asked to sort each entity into whether that entity should have access or not have access to satellite imagery. We aimed to evenly split locations and activities across the three activity types ("innocuous", "doxxing", "illegal") per our private activities codebook.

Next, we asked participants to choose a statement about satellite imagery access that they most agreed with out of four possible statements: (1) "Satellite images should be available to everyone for free", (2) "Access to satellite imagery should cost money and depend on what the user is requesting the imagery for", (3) "The U.S. government should be the only ones allowed to access satellite imagery", and (4) "No one should have access to satellite imagery". Statement (2) corresponds with the typical practices of commercial satellite imagery today, and Statement (1) corresponds with current trends in geospatial data (Section 2). We then showed a set of photos taken with a drone over a parking lot ranging from 1cm to 1m spatial resolution, and participants indicated the highest spatial resolution that they would be comfortable with being taken of them. We then asked what temporal resolution they were comfortable with assuming their previous choice of spatial resolution, ranging from "every second" to "never".

Demographic Section. We included an attention check right before the demographic section, which every participant passed. Full

Table 1: Breakdown of participant demographics by gender, age, race/ethnicity, and political affiliation.

Gender		Age		Race/Ethnicity		US Political Affiliation	
Man	64.6%	25-34	16.2%	White	82.9%	Democrat	62.6%
Woman	35.4%	35-44	51.5%	Black or African American	8.1%	Independent	19.2%
		45-54	20.2%	Asian	5.1%	Republican	17.2%
		55-64	10.1%	Mixed	4.0%	Libertarian	1.0%
		65+	2.0%				

lists of options are included in the full survey instrument in Appendix A.

4.3 Analysis Techniques

For all free responses, we used grounded theory to first take shorthand notes of all conceptually new ideas people brought up, then sorted these into a set of more overarching themes. One author proposed a codebook based on these notes, and then two additional authors (along with the first) discussed themes until consensus was reached. The codebook can be found in Appendix B. Two authors coded each qualitative analysis for which we discussed results, and had an inter-rater reliability of 95.5% agreement. Cohen's kappa was $k = 0.885$, indicating strong agreement [15].

4.4 Limitations

Crowdsource responses do not necessarily represent society as a whole, or even a specific region, like the United States. Rather, crowdsource responses at most represent the population participating in the crowdsourcing platform. Additional considerations and tensions might arise if studying other demographic groups. We recommend the study of additional populations in the future, including residents outside of the United States and historically marginalized populations.

MTurk is the only crowdsourcing platform allowed for use by our institution at this time, and hence we used MTurk. While we were initially skeptical about the use of MTurk, given prior anecdotes as well as our own prior experience with MTurk, all authors were impressed by the quality, relevance, and thoughtfulness of all free-responses in our survey. To increase the likelihood of high quality responses, we filtered for above 98% approval ratings on MTurk. To further indicate that participants were engaged, every participant passed the attention check at the end of the survey, which we designed to not be obvious for those skimming. Since there was not an option on MTurk to choose a demographically representative sample, the MTurk demographics were not representative of the overall demographic proportions in the United States. Our respondents were skewed toward men, white, and Democrat political affiliation.

For the drone images we showed participants in the survey, we could not show past 5cm spatial resolution on some images due to drone image quality at the height needed to capture the necessary physical space. This limited what set of images we could show participants, while attesting to the impressiveness of the high spatial resolutions of commercial satellite imagery.

5 ETHICAL CONSIDERATIONS

Performing the survey was determined to be exempt by our institution's IRB. Our participants were kept anonymous, and the most sensitive questions we asked were the demographics questions. Our IRB had access to a summary of the survey protocol. Taking drone images to include in our survey was determined to not be human subjects research by the IRB. We obtained all necessary permissions for using drones and followed all relevant Federal Aviation Administration (FAA) regulations. We only took drone images in confined spaces, so no unintentional bystanders' privacy was violated while imaging. We provided each car owner and human participant an individual waiver to sign.

Since our ultimate goal is not just to understand what factors influence people's privacy and utility considerations related to satellite imagery (RQ1), but to also explore approaches for protecting privacy while offering utility (RQ2), our ongoing, follow-on work (in collaboration with the School of Law at one of our institutions) is to determine the best strategies for communicating our findings and recommendations to policy makers and others.

6 SATELLITE SURVEY RESULTS

We now turn to presenting our results. For each subsection of results, we include key considerations that we incorporate into our suggestions for future satellite imagery practices (Section 7). Analysis of demographic differences is included in Section 6.6.

We present descriptive data and statistical analyses in order to describe the factors influencing privacy versus utility considerations for the sample studied here. We do not suggest all populations would have the same responses. Instead, even if these considerations and tensions only apply to a subset of people, those people are important and must be considered.

6.1 Satellite Image Awareness

Before turning to our specific research questions, we first sought to establish a baseline understanding of the degree to which respondents are aware of satellite images and their practices. Only 32% of respondents knew that commercial satellites existed. Given a set of options between once a second and once a year, 58% of respondents thought that a satellite company could image the same location every day at most (either daily, weekly, monthly, or yearly). As stated in Section 2, some commercial satellites have already exceeded this once per day capability; some can image locations up to 15 times a day [38] and others can create a real-time video for up to two minutes [51]. Given a set of images of resolution options, 91% of respondents correctly guessed that the best commercial satellite spatial resolution is around 15cm. This could be because 15cm was the highest resolution option we presented to participants due to drone imaging limitations.

Guesses about how much one satellite image costs ranged from $US1-20,000,000. The median guess was $100, which is similar to the current cheapest prices; it cost us around $175 for a 75cm resolution image of over 9 square miles (Section 3.2), but the cheapest imaging that were less recent and lower resolution were under $50.

> **Consideration 1:** Lack of awareness of temporal resolution capabilities of satellite imagery means some privacy expectations do not align with possible privacy violations.

6.2 Benefits and Harms

We next explore how respondents discuss the benefits and harms of satellite images to begin to answer RQ1. Recall from Section 4 that to avoid priming, we ask about benefits before harms and do not mention privacy.

We first examine the harms participants considered, and find that the majority of participants consider the privacy risks of this technology in their responses. In particular, 52% of respondents explicitly used the words "private" and "privacy" in their responses as potential harms. Overall, our qualitative analysis (described in Section 4.3) led to the following categories of *harms*:

- **Invasion of privacy**. This includes monitoring day-to-day activities or specifically on personal property.
- **Security**. Participant 17 (P17) believed that satellite images "being in the possession of third parties means that any information that can be captured by a commercial satellite is no longer safe, secure, or private."
- **Facilitating Crimes**. Respondents mention facilitating both terrorism and burglaries.
- **Military Operations**. One respondent mentioned that it could help the military plan out a bombing.
- **Surveillance**. This theme includes monitoring of activities by the US government, foreign governments, and civilians. Stalking was specifically mentioned as a potential risk.
- **Law enforcement Abuse**. P14 was concerned that law enforcement "could get images without having to get a warrant."
- **Natural Resource Misuse**. Specifically, companies using satellite imagery to find natural resources.
- **Unwanted Advertising**. Companies could target advertisements based on what is in someone's backyard, such as a pool-cleaning service for pool owners.
- **Incorrect Identification**. Misidentifying items based on satellite images.
- **Compliance**. An example is "homeowners being fined for the condition or reshaping of their roofs" (P53). As seen in Section 2, the French government has already carried out one such application, fining its citizens for unregistered pools.
- **AI Integrations**. This means using AI to facilitate the above harms. Only one respondent mentioned this.

Possible benefits of satellites mentioned tended to be more varied and specific than the harms posed. It is clear that respondents were able to consider the possible utility of these satellite images along with their harms. We split *benefits* into the following categories:

- **Mapping**. 21% of people mentioned mapping use cases as a potential benefit, such as for improved map accuracy, logistics, or "to see if an attraction is crowded so we know to go another day" (P66).
- **Real Estate and Infrastructure**. Providing additional information for purchasing real estate, facilitating city planning, evaluating housing density, and understanding traffic patterns are some examples people mentioned. 35% of respondents mentioned this type of benefit.
- **Government Accountability**. Some respondents mentioned how more access helped prevent government abuse, including this response: "deforestation ramped up drastically in Brazil during Bolsonaro's reign. I think satellite images from commercial enterprises could keep people informed so maybe they could put pressure on governments" (P14).
- **Legal Compliance and Crime Detection**. P79 explained that some of their previous tasks on MTurk were to evaluate satellite imagery, including looking for illegal oil refineries.
- **Targeted Advertising**. Some respondents discussed how looking at people's backyards could help companies sell products, such as solar panels.
- **Emergency Response**. Respondents mentioned how satellite images could help locate missing entities such as ships, people, and cars. P79 explained that some of their previous tasks on MTurk were to find "illegal oil refineries, whales and even that missing Malaysian airliner". Others mentioned using images to check structures for damage or respond to natural disasters.
- **Studying Natural Phenomena**. Examples include climate change, biodiversity, and volcanoes.
- **More Information**. This includes information in general and not about a specific topic, as P45 states: "Any data is good data. The more I see, the more I know".
- **Surveillance**. Either government or civilian entities collecting information about government or non-government entities.
- **Agriculture**. Examples given include planning out land use and monitoring crops.

Some benefits and harms overlap, highlighting how privacy and utility can be in tension between respondents. For example, advertising, government surveillance and information gathering all fall under both potential benefits and harms.

> **Consideration 2:** Privacy violation is a concern of potential satellite harms.

> **Consideration 3:** There is disagreement between whether some applications are harmful or beneficial.

6.3 Privacy versus Societal Benefits of Satellites

We further investigate RQ1 through analysis of the would-you-rather questions. Quantitative analysis of participants' choices, along with qualitative analysis of their explanations, allowed us to more deeply explore how they weigh privacy versus utility, and whether there are tensions between the two. The results, along with the scenario questions, are summarized in Table 2. For each pair of scenario questions, we ask "Would you rather satellites have both of these capabilities, or neither of these capabilities?".

6.3.1 Scenarios Question 1. This first question addresses activities that are measurable from satellites images if car presence is observable in the images: "Consider scenarios A and B. A: Satellite images are used to track the number of cars at a hospital, which helps with predicting levels of disease in the area. B: Someone calls in sick to work. To check whether they are at home, their employer takes a satellite image over their home and observes whether their car is there." Only 21% chose to allow both. An example of why someone chose both is for "the greater good" (P60). Others cited that there is no reasonable expectation of privacy: "Public is public. Get a garage if you don't like it" (P79). Of the 79% who chose that neither should be allowed, many deemed monitoring employees unethical or the privacy violation to be too high. For example, one response was that "The benefits of A do not outweigh the invasion of privacy afforded by B" (P17).

6.3.2 Scenarios Question 2. Scenarios in this question require observing the presence of humans or objects, with scenario D posing monetary benefits: "C: Someone wants to know whether their former romantic partner is having any visitors to their house, and uses a satellite image to detect how many people are gathered in their former romantic partner's backyard. D: Someone's backyard catches fire, and their insurance provider uses a satellite image to confirm the items that were lost due to the fire, which ends up giving the fire victim more money than expected". Only 26% chose to allow both. Someone didn't believe that the privacy infringement could hurt the victim: "The spying in this case will not lead to a privacy infringement that can hurt someone and the fire damage issue is relevent" (P3). Another respondent argued that "Gathering information about an ex and settling insurance claims are both important" (P84). The 74% who chose to deny both cited the threat of stalking and/or spying. Others cited their personal stance on privacy: "I would rather give up the ability of an insurance company to better pay out losses than give out private information" (P25).

6.3.3 Scenarios Question 3. Both scenarios in the third question require observing and identifying individuals: "E: Satellite images are used to detect what a well-known celebrity is doing in their backyard. F: Satellite images are used to locate a hiker that went missing in the mountains." 58% of respondents chose to allow both scenarios, with reasoning such as the value of saving a human life, as well as the current privacy expectations of celebrities: "A celebrity does not expect privacy" (P84). Some of those who disagreed mentioned the high value of privacy, such as: "Satellite images to find a hiker would be good, but not if it comes with violations of other people's privacy" (P14).

6.3.4 Scenario Question 4. We included a fourth scenario question that wasn't as closely tied to individual privacy asking about using satellite imagery for conservation versus people using it to find species for illegal hunting. There was overall 53% agreement to allow both. This question was used as reference to compare with the scenario pairs that tied more to individual privacy. This fourth question was the most evenly split in responses across all scenarios.

6.3.5 Scenario Commonalities. Across all scenarios, there were several commonalities in how people weighed privacy concerns versus potential benefits. For example, respondents justified allowing both or neither scenarios by saying that there are better and cheaper ways to achieve the same goal. Respondents cited privacy in choosing either option for each scenario, saying that the social benefits of a scenario are more important than privacy or vice versa.

> **Consideration 4:** There exist temporal and spatial resolutions and application domains such that there is no consensus on whether that resolution of satellite imagery should be allowed.

> **Consideration 5:** Whether people prefer satellites to be allowable at a given resolution depends heavily on the use case in question. If not possible to conditionally choose which satellite use cases are allowable, potential privacy threats may outweigh societal benefits of satellites at certain resolutions.

6.4 Comfort with Satellite Imagery

We gauged the commercial satellite capabilities and use cases that respondents were comfortable with to further understand what factors influence privacy versus utility tradeoffs (RQ1).

6.4.1 Resolution Capabilities. We showed respondents drone images we took of volunteers that were downsampled at different spatial resolutions, ranging from 1cm to 1m. Most respondents said they were comfortable with images being taken of them between 1cm and 15cm, which is equivalent or higher than current commercial satellite capabilities [23]. However, 84% of respondents were not comfortable with these spatial resolutions being taken more than once a day. And 36% of respondents were not comfortable with the images being taken more than once a year. In other words, people are comfortable with current spatial resolution capabilities but *not* when combined with current temporal resolution capabilities. See Appendix D for a summary of resolution comfort results.

Interestingly, in general the higher the temporal resolution comfort, the higher the spatial resolution comfort as well. We expected that those who chose higher spatial resolution would choose a lower temporal resolution, but these results show that this is not the case. We hypothesize that this is simply due to people's general privacy preferences or expectations: someone who has lower privacy expectations or less of a preference for privacy is comfortable with having both high spatial and temporal resolution images taken of them.

> **Consideration 6:** Many people are not comfortable combining very high spatial resolution with very high temporal resolution. Temporal resolution and spatial resolution should be considered in unison.

Table 2: Scenarios with individual or societal benefits versus scenarios that violate privacy. Percent of respondents who chose to allow both, organized by demographic. Full scenario questions are included in Section 6.3.

Scenario Pairs	Overall	Women	Men	Democrat	Republican
Scenario A: Detecting cars in hospital to track disease. Scenario B: Employer checks employee's car who calls in sick.	21%	14%	25%	19%	35%
Scenario C: Former romantic partner looking into backyard for visitors. Scenario D: Confirm items lost during fire for insurance.	26%	26%	27%	16%	65%
Scenario E: Detecting celebrity's activities. Scenario F: Locating a missing hiker.	57%	60%	56%	45%	94%

Table 3: Percent of respondents who think it is acceptable for entities to have access to satellite images. Overall percentage along with percentages by demographic (political affiliation and gender). W is women, M is men, D is Democrat, R is Republican.

Entity	Overall	W	M	D	R
Agriculture Industry	82%	74%	86%	76%	100%
US Government	79%	71%	83%	77%	82%
Police	71%	69%	72%	61%	94%
Non-profits	61%	51%	66%	56%	71%
World governments	47%	23%	61%	53%	35%
Finance industry	37%	29%	42%	32%	53%
Employers	19%	9%	25%	16%	41%
Romantic partners	16%	6%	22%	8%	47%
Children	8%	6%	9%	8%	6%
Convicted criminals	7%	6%	8%	6%	6%

> **Consideration 7:** Those who are comfortable with higher temporal resolution also tend to be more comfortable with higher spatial resolution.

6.4.2 *Use Cases.* Results from the bucket-sorting activity further illustrate how different factors, such as the use case, affect evaluations of privacy. Tables 3 to 5 summarize these results, showing what percent of respondents deemed each bucket acceptable to image or be imaged by.

The bucket deemed least acceptable on average was imaging people while sunbathing (4%), and the most acceptable was imaging a rainforest (96%). Even in the case of illegal activities, not everyone thought it was acceptable for satellites to image them; only 19% overall found it acceptable to image people doing illegal drugs in their backyard. 64% thought it was acceptable to image people doing illegal drugs in public, which attests to the privacy expectation people have in their backyards. Overall, only 11% thought it was acceptable to image backyards. Whereas legal activities that could be seen as doxxing material was on average acceptable by 33% of respondents, imaging illegal activities was on average acceptable by 65%. In fact, satellites are already used to detect illegal activity, such as IIU fishing [50], and as one respondent said, illegal oil refining. In the "innocuous" category of activities, imaging of satellites was still not deemed acceptable by all respondents. On average, these activities were deemed acceptable by 46% of respondents.

Table 4: Percent of respondents who think it is acceptable for locations to be imaged by a satellite.

Location	Overall	W	M	D	R
Rainforest	96%	91%	98%	97%	94%
Illegal business	84%	77%	88%	81%	94%
Grocery store	59%	37%	70%	55%	76%
Native lands	54%	46%	58%	50%	71%
The White House	53%	57%	50%	48%	53%
Religious center	33%	23%	39%	32%	47%
Adult-only store	31%	17%	39%	27%	59%
Mental health clinic	28%	17%	34%	24%	47%
Playground	15%	20%	13%	6%	29%
Backyards	11%	6%	14%	8%	24%

Table 5: Percent of respondents who think it is acceptable for activities to be imaged by a satellite.

Activity	Overall	W	M	D	R
Car accidents	95%	94%	95%	92%	100%
Illegal fishing	81%	74%	84%	85%	76%
Building w/o permit	78%	74%	84%	85%	76%
Driving	67%	60%	70%	66%	59%
Illegal drugs (public)	64%	60%	66%	56%	76%
Visiting jewelry store	26%	26%	27%	21%	47%
Illegal drugs (backyard)	19%	20%	19%	15%	35%
Extramarital affairs	12%	9%	14%	6%	35%
Meeting friends & family	9%	6%	11%	6%	18%
Sunbathing	4%	3%	5%	3%	12%

> **Consideration 8:** Acceptability of imaging varies by use case, but there is no universal agreement on any category of activity, whether or not it's illegal.

6.5 Should We Democratize Satellite Image Access?

We begin to explore RQ2 by investigating respondents' preferences for regulatory or legislative approaches to protect individual privacy against commercial satellite imagery. Results are summarized in Table 6. 68% respondents most agreed with Statement 2, that access to satellite imagery should cost money and depend on the use case, which is the common-practice today. Only 12% agreed with making imagery widely available; this low agreement with Statement 1 goes against movements from the geography field to increase image access [9, 16, 17, 66]. The remaining 20% didn't want commercial satellites to be allowed at all, either choosing that only the U.S. government should have access or no one should have access. Some factors respondents mentioned in making their decisions were:

- Whether there could be conditional access, such as not being able to image private property.
- The societal benefits outweighing the harms (and vice versa).
- Privacy expectations.
- The value of information.
- Which entity a respondent does not trust.
- Preventing abuse.
- Fairness. For example, "let the market value it fairly" (P62). Others thought it would be most fair to give everyone access so that it was not only accessible to the rich and powerful.

> **Consideration 9:** Some people believe that we should regulate who has access to satellites by charging money for images or granting access based on use case.

> **Consideration 10:** Some people believe there should be additional specifications and rules in place to prevent misuse of satellite imagery.

> **Consideration 11:** Some people believe that paywalls on imagery may prevent abuse by civilians but promote abuse by the government and other powerful and wealthy entities.

6.6 Demographic Differences in Responses

On an exploratory basis, we also investigated how respondents' demographics might impact their perceptions of satellite imagery. Before suggesting legislative, regulatory, and technical solutions, we wanted to understand whether differences in privacy preferences vary significantly by people's lived experiences and personal ideologies. If one groups' lived experience leads them to experience a privacy harm much more than another, then this difference should be considered.

We chose to investigate demographic differences by gender and political affiliation because we had theoretical reason to believe there might be relevant experiences or ideologies that affect perceptions of privacy amongst these groups [7, 62]. Within political affiliation, we compared between Democrats and Republicans. We excluded Independents from analyses because this group may lack a common ideology, and we had less theoretical motivation to investigate this group. Within gender, we compared between men and women only since there were no responses for other genders.

Commercial Satellite Imagery Awareness by Gender and Political Affiliation. 39% of men claimed to be aware of commercial satellites before taking the survey, versus only 20% of women. 29% of Democrats and 35% of Republicans were aware. We ran 2 independent-samples t-tests total to understand differences in acceptance labels across demographics.

Use Case Acceptability by Gender and Political Affiliation. Tables 3 to 5 show use case responses organized by demographics. There are notable differences in responses by gender and by political affiliation. Overall, men found 48% of all buckets acceptable, compared to women who found 39% of buckets acceptable. We performed a t-test and found that the average acceptance level between genders across all buckets was statistically significantly different ($p < 0.05$). Some use cases produced especially pronounced gender differences in acceptability. For instance, 70% of men found imaging grocery store parking lots acceptable versus only 37% of women. While we do not know the cause, it could be because that among heterosexual couples, women spend more time grocery shopping and thus would me more affected by imaging grocery stores [53]. The most pronounced difference in entities deemed appropriate was that 61% of men thought it was acceptable for other world governments to access this imagery, as opposed to just 23% of women.

Republicans on average found 56% of buckets acceptable, while Democrats found 42% of buckets acceptable. We performed a t-test and found that the average acceptance level between political affiliation across all buckets was statistically significantly different ($p < 0.05$). Between Democrats and Republicans, the largest difference in opinion was whether romantic partners should have access to satellite images; 47% of Republicans found it acceptable versus 8% of Democrats. Democrats and Republicans disagreed more than men and women in what is acceptable to image (17% average disagreement versus 11%).

Policy Recommendations by Political Affiliation. For the statement questions in Section 6.5, shown in Table 6, 88% of Republicans most agreed with Statement 2, which is to control satellite image access by price and use case. In contrast, only 65% of Democrats chose this statement.

Scenario Pair Acceptability by Political Affiliation. The largest differences in scenario acceptability were between Republicans and Democrats. Republicans were dramatically more likely than Democrats to say both scenarios are acceptable. There was almost a 50% difference in acceptability between Republicans and Democrats on scenario questions 2 and 3 (Table 2).

Resolution Acceptability by Gender. For assessing comfort of spatial and temporal resolutions, results followed similar patterns of women wanting more privacy (lower spatial and temporal resolutions) than men. There was not as clear of a pattern in resolution comfort between Democrats and Republicans.

Table 6: Agreement of different satellite image access statements, per Section 6.5.

Scenario Pairs	Overall	Women	Men	Democrat	Republican
Statement 1: Satellite images should be available to everyone for free.	12%	3%	17%	11%	12%
Statement 2: Access to satellite imagery should cost money and depend on what the user is requesting the imagery for.	68%	66%	69%	65%	88%
Statement 3: The U.S. government should be the only ones allowed to access satellite imagery.	13%	20%	9%	15%	0%
Statement 4: No one should have access to satellite imagery.	7%	11%	5%	10%	0%

Consideration 12: People's lived experiences and personal ideologies affect their privacy perceptions of satellite imagery. For example, overall, women wanted more privacy (lower spatial and temporal resolutions) than men.

Consideration 13: An average perception of acceptability is not enough; demographics that are affected most for each use case should be considered, as well as the distribution of political affiliations of citizens.

6.7 Study Participants' Solutions

Throughout the survey, study participants brought up possible legislation, regulation, and other limitations for satellite imagery in the free responses. One participant suggested that there should be public records of requests along with every image request. Another said there should be increased punishment of people if they use satellite imagery to commit a crime, such as stalking. With the insurance scenario, someone said it should be allowed with consent. One participant who said that satellite images should be available depending on use case said that "satellite imagery could be super useful, but there need to be guidelines. For instance, you cannot buy satellite imagery to someone's private home" (P1). Another participant suggested image requesters must pass background checks. Others suggested location-based controls, such as preventing imaging of schools, parks, and personal property. We discuss some of these solutions further in Section 7.

Consideration 14: Listening to residents might yield ideas for regulatory and technical solution to prevent satellite image privacy harms.

7 SYNTHESIZING RECOMMENDATIONS

Informed by the results in Section 6, we now turn to RQ2 and our synthesis of regulatory, legislative, and technological recommendations, as well as future directions. As exemplified by survey respondents in Section 6.2, commercial satellites offer many existing and potential benefits. It is both unhelpful and unrealistic to prohibit their use in the United States or internationally. But there are some approaches that multiple stakeholders could take to prevent or respond to possible misuse. We refer up to considerations mentioned in Section 6 by mentioning the Xth consideration as "**C**X". While our expository focus is on the United States, we believe that all countries and jurisdictions should consider similar issues.

7.1 For Regulators and Legislators

Spatial and Temporal Constraints. There is an argument to be made for most temporal and spatial resolutions. For example, legislators may decide that the resolution at which you can identify cars outweighs the potential harms of some privacy issues, but that a resolution sufficient to identify humans is too high. In 2014, U.S. legislators relaxed limits on commercial panchromatic (black and white) imagery to 25cm [37]. As pressure from the commercial sector may grow to further lower this limit, legislators should seek input from citizens when deciding on any new regulations (**C2, C12-14**). Non-resolution-based methods for protecting privacy and sensitive information include blurring specific portions of high-resolution satellite imagery, such as individuals' faces or military bases. We also propose mosaicking multiple images together (e.g., [55]) over a region so that it does not exactly depict a specific place and moment in time as a means to protect privacy.

As mentioned in **C6**, it is not enough to just consider spatial resolution; temporal resolution should also be considered. Whether the public — anyone who purchases or views satellite imagery for something other than governmental purposes — should have access to daily, weekly, monthly, or annual imagery are all questions to consider. As imagery at more frequent time intervals is collected, making near-real-time imagery of Earth a possibility, legislators should also consider the utility of delayed release of images. This can help avoid instrumentalization of data for near-real-time combat or intelligence purposes, as suggested by geographers [9]. However, desirable exceptions to time delays and spatial/temporal resolution constraints might include emergencies, natural disasters, and search and rescue, such as locating a missing person, ship, or other entity (Section 6.2). In such situations, tiered user systems, as with Norway's International Climate and Forests Initiative Satellite Data Program, which makes available 3m Planet imagery available to vetted users, may make sense [48].

Other possibilities for restricting access include a Geospatial Authorization Model (GSAM), which limit access to view, zoom-in, overlay, and identification modes (e.g., [2]), or virtual data enclaves in which users access and analyze data in a virtual/remote environment as opposed to on their own local desktop [26].

Other Constraints. It is also not enough to just consider resolution constraints as if satellite imagery is in its own data silo. Geolocation data separate from satellite imagery, such as that which is gathered from people's mobile phones and sensing devices such as smartwatches, can augment the inferences that can be made about individuals from satellite imagery. The analysis of such data is sometimes referred to as "social sensing" [64], drawing parallels with remote sensing. Artificial intelligence-assisted analysis of big Earth observation and social sensing data, a field called GeoAI, is generating increasing interest from scholars [30], particularly in China [10], where government and police agencies demonstrate high interest in new surveillance technologies. Within the security and privacy community, it is well-known that information from multiple sources can be combined to learn information not available in either source directly (e.g., [61]). Whether or not satellite imagery can resolve an individual, other markers, such as a vehicle, may be identifiable and then combined with social sensing data to profile and track someone. We recommend that legislators work with researchers to understand what additional information leakage there may be when combining satellite imagery with social sensing data.

Conditional Access. Most respondents preferred that access to satellite imagery vary by use case and cost (**C9, C10**), but there is disagreement in what constitutes beneficial or harmful applications (**C3, C4, C8**). Differences in responses among individuals and statistically significant differences in responses by demographic group (Section 6.6) indicate that it could be helpful for legislators to hear feedback from a diverse set of perspectives and lived experiences (**C7, C12-14**). If conditional access or blurring out only some information, like private property, is not possible, then possible privacy harms may outweigh beneficial satellite imagery use cases at certain resolutions (**C5**).

Logging Information. When satellite imagery becomes available to the public, the government could require that resolutions are below a certain threshold, and that there be a centralized, freely available repository of all non-governmental image requests as recommended by a survey participant (Section 6.7). As with other computer security and privacy domains, the awareness that adversarial actions may be logged could serve as a deterrent to some adversarial actions and thus could be a component in a multi-pronged approach for protecting individual privacy.

Paywalls. The state of commercial satellites today may support the idea that "we should just give up on privacy", at least in the context of remote sensing; because militaries in other states are using it anyways, there may be no way to protect people. However, if data is free and publicly available, this minimizes costs for adversaries (**C9-11**). The barrier of image cost may mitigate some harms, such as incentives for using satellite images as a tool for burglary. For example, free information about whereabouts on social media page aided in burglaries of high-profile celebrities [35]. Some survey respondents also mentioned how they preferred a paywall (**C11**). Privacy researchers and geographers should communicate their differing viewpoints for and against making satellite imagery free and widely available. We aim to begin this conversation with this work and also with our own follow-on discussions with geographers.

7.2 For Companies and Designers

When developing higher spatial, temporal, and spectral resolutions in future satellite imaging technologies, both governments and industries should weigh whether these higher resolutions are necessary to achieve goals people have for their satellite imagery use case, and if that use case might itself violate individual privacy.

7.3 For Researchers and Privacy Advocates

Increasing Awareness and Consent. Per **C1**, people should be made more aware of the current capabilities of satellites, as well as that purchasing commercial satellite imagery is possible for individuals. If not to fix the problem of surveillance and privacy threats, knowing that an image can be taken over backyards and even at night will help people change their own expectations of privacy and possibly their behavior. Informed by the security and privacy community's general advocacy for the value of informed consent, we suggest that there be a way for people to sign up to be notified or have their property blurred out when a satellite takes images over their area (or warning them before). More research on implementation and user interest is needed.

Future Research. Our work focuses on RGB images that are perpendicular to the ground. Future work should explore the spectrum of additional privacy concerns introduced by off-nadir, SAR, and near infrared imagery (discussed in Section 2), as well as complementing satellite imagery data with other data (Section 7.1).

Researchers currently use machine learning (ML) to evaluate satellite imagery for myriad purposes, from predicting poverty [31] to evaluating shorelines [39] to detecting disease activity [42]. However, with benefits also comes possible privacy violations; it is already possible to identify cars and groups of people in satellite imagery using ML [25]. Future research could explore both the possible harms that ML brings in the context of satellite imagery, but also how to use it as a tool to automatically blur or otherwise obfuscate satellite imagery without simultaneously revealing important information, as a company accidentally did by only blurring out sensitive military locations [34]. Future work could also explore what aspects of imagery are private in what contexts, since external circumstances such as war can change what is deemed private for a given time and location. For another application of ML, the ambiguous potential of deepfakes, which may paradoxically protect individual privacy by exacerbating doubts regarding photorealistic information, should also be considered carefully.

We also encourage the security and privacy research community to consider new technical defenses. Extending the previously-discussed notion of virtual data enclaves [26], one defensive strategy might be the creation of services that answer queries about geographic locations without revealing raw imagery. More challenging, though of potential intellectual interest, is the study of ways to protect (encrypt) satellite imagery such that recipients of those protected images can perform some computations over those images (e.g., detect if an animal is present) on their own devices without simultaneously having access to the entire contents of the raw image; such a direction is akin to research focused on other forms of search over encrypted data, e.g., [1, 18, 59].

Finally, the emergent subfield in geography of Critical Remote Sensing can also be expanded to build on analysis of not only the politics and economics of the growing commercial remote sensing industry [5], but its ethics and norms, too. Comparative work examining the regulatory and cultural contexts surrounding satellite imagery and individual privacy in other countries [10] could also prove illuminating and help identify areas of international consensus.

8 CONCLUSION

In this paper, we explored privacy threats and concerns of commercial satellites in multiple phases; first, we brainstormed and qualitatively analyzed possible threats of commercial satellite imagery. Second, we surveyed people living in the U.S. about their awareness and concerns towards satellite imagery. We found that there was insufficient awareness about commercial satellites and that people's privacy expectations and preferences often conflicted with current commercial satellite practices, and may conflict even more with future commercial satellite practices. Third, we proposed possible mitigations of potential privacy violations addressed to multiple stakeholders. High-resolution commercial satellites may change how we understand surveillance and our expectations of privacy. Before spatial and temporal resolution improve even more, it is crucial to study these topics and begin holding conversations with legislators, industry, and the public that is being watched from above.

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A SURVEY QUESTIONS

[Consent Form] We are researchers at the University of Washington (UW) studying the relationship between people and satellites in space. This study was reviewed by the UW Institutional Review Board (IRB) and deemed exempt because it involves no more than minimal risk and meets other criteria. Your responses to this survey will be anonymized. Data from this survey will be stored securely and kept confidential. Your participation in this study is voluntary. You may withdraw your participation at any time. If you have questions about this study, you may contact the PI at satellites@cs.washington.edu. You may also contact the UW Human Subjects Division (HSD), which manages IRB review, at hsdinfo@uw.edu.

I am at least 18 years old, I have read and understood this consent form, and I agree to participate in this online research study. ○ Yes ○ No [End survey if no]

Are you an employee of the University of Washington, family member of a UW employee, or UW student involved in this particular research? ○ Yes ○ No [End survey if yes]

[Filtering] For this survey, we require participants to be above a certain level of corrected vision and computer screen quality, since some later questions involve evaluating images. How many people are there in the image below? (Answer in the empty box below the picture) [Photo shown is Figure 3] ______ [End survey if answer is not 5]

Figure 3: Photo we show to respondents to filter for vision impairments

[Introduction] This study has 8 sections and we estimate it will take 20 minutes or less

[Filters for definition comprehension] In the following questions, we will consider imagery taken from directly above (perpendicular to) the ground, such as what satellites in outer space might capture. We define this as the “satellite view". We list some examples below of images that are "satellite view" and images that are not "satellite views". This is a satellite view, since the image is taken directly above (perpendicular to) the ground: [Survey includes example of an image taken from satellite view] This is not a satellite view: [Survey includes example of an image taken *not* from satellite view]

Is the image below a "satellite view" image? (To move on to the remaining questions, you must answer this question correctly.) [Image shown that is not a satellite view] ○ Yes ○ No [End survey if yes]

Is the image below a "satellite view" image? (To move on to the remaining questions, you must answer this question correctly.) [Image shown that is a satellite view] ○ Yes ○ No [End survey if no]

Is the image below a "satellite view" image? (To move on to the remaining questions, you must answer this question correctly.) [Image shown that is not a satellite view] ○ Yes ○ No [End survey if yes]

[Awareness and Perception] Commercial satellite companies collect images from satellites in space and sell these images to non-governmental individuals, non-governmental organizations, and governments for a variety of applications, including agriculture, defense, and scientific research. Individuals, such as you, are allowed to purchase these images.

Before this survey, had you heard of commercial satellites selling images of the Earth to non-governmental individuals and organizations? ○ Yes ○ No

Do you see any ways that the use of commercial satellite images could be beneficial? Please list them below. (If you cannot think of any, please enter "None"). [Free-response text] _______

Do you see any ways that the use of commercial satellite images could cause harms? Please list them below. (If you cannot think of any, please enter "None"). [Free-response text] _______

Below is the same image of a parking lot but at different resolutions. Which of the following images do you think represents the highest-resolution commercial satellite camera when the satellite is taking the image from space? ○ [Image of cars in parking lot downsampled to 10m resolution] ○ [Image of cars in parking lot downsampled to 3m resolution] ○ [Image of cars in parking lot downsampled to 1m resolution] ○ [Image of cars in parking lot downsampled to 15cm resolution]

Suppose someone wants to see how the parking lot from the previous question changes across time. How often do you think a single commercial satellite company can take an image of the same parking lot? ○ Every year ○ Every month ○ Every week ○ Every day ○ Every hour ○ Every minute ○ Every second

How much do you think it costs for an individual to buy one satellite image (in US dollars)? For reference, one satellite image could be over 10 square miles of the earth. [Number] _______

[Scenarios] Satellite images have a variety of capabilities to capture different activities, places, and people. Below, you will see pairs of hypothetical satellite capabilities. For each pair, decide whether you would prefer satellites to have both capabilities, or whether you would prefer satellites to have neither of these capabilities.

Consider scenarios A and B. A: Satellite images are used to track the number of cars at a hospital, which helps with predicting levels of disease in the area. B: Someone calls in sick to work. To check whether they are at home, their employer takes a satellite image over their home and observes whether their car is there. Would you rather satellites have both of these capabilities, or neither of these capabilities? ○ Both scenarios should be allowed ○ Neither scenario should be allowed

Why did you choose your answer to the previous question? [Text box] _______

Consider scenarios C and D. C: Someone wants to know whether their former romantic partner is having any visitors to their house, and uses a satellite image to detect how many people are gathered in their former romantic partner’s backyard. D: Someone’s backyard catches fire, and their insurance provider uses a satellite image to confirm the items that were lost due to the fire, which ends up giving the fire victim more money than expected. Would you rather satellites have both of these capabilities, or neither of these capabilities? ○ Both scenarios should be allowed ○ Neither scenario should be allowed

Why did you choose your answer to the previous question? [Text box] _______

Consider Scenarios E and F. E: Satellite images are used to detect what a well-known celebrity is doing in their backyard. F: Satellite images are used to locate a hiker that went missing in the mountains. Would you rather satellites have both of these capabilities, or neither of these capabilities? ○ Both scenarios should be allowed ○ Neither scenario should be allowed

Why did you choose your answer to the previous question? [Text box] _______

Consider scenarios G and H. G: Satellite images are used to detect and find endangered species based on tracks the species leave on the ground, which helps with conservation efforts. H: Satellite images are used to detect and find endangered species, based on tracks the species leave on the ground, which people use to illegally hunt the endangered species. Would you rather satellites have both of these capabilities, or neither of these capabilities? ○ Both scenarios should be allowed ○ Neither scenario should be allowed

Why did you choose your answer to the previous question? [Text box] _______

[Comfort] Imagine that there were commercial satellites that could take images that capture fine-grained details, and could take images multiple times per hour. Imagine that these very high resolution satellite images do not cost any money. Consider these very high resolution satellites when you answer the bucket-sorting questions on the following pages.

Move the following location boxes based on whether you think it is appropriate for very high resolution satellites to image them. (Boxes will automatically expand as needed to fit additional entities) [Respondents must sort the following options into “Yes appropriate” and “Not appropriate”]: Mental health clinic parking lot, Grocery store parking lot, Kindergarten playground, Location of illegal business, Religious center parking lot, Rainforest, Backyards, The White House and surrounding areas, Native lands, Adult-only store parking lot

Move the following entities into two buckets for whether they should have access to very high resolution satellite imagery. (Boxes will automatically expand as needed to fit additional entities) [Respondents must sort the following options into “Yes Access” and “No Access”]: The United States government, Governments around the world, All children, Agriculture industry, Finance industry, Non-profit organizations, Convicted criminals, Romantic partners, Police, Employers

Move the following activities into whether you think it is appropriate for powerful satellites to image them. (Boxes will automatically expand as needed to fit additional entities) [Respondents must sort the following options into “Yes appropriate” and “Not appropriate”]: Driving, Building without a permit, Sunbathing, Someone using illegal drugs in their backyard, Someone using illegal drugs in public, Car accidents, People having extramarital affairs, Fishing illegally, Meeting with friends or family, Visiting a jewelry store

Choose the statement that you most agree with. Statement A: Satellite images should be available to everyone for free. Statement B: Access to satellite imagery should cost money and depend on what the user is requesting the imagery for. Statement C: The U.S. government should be the only ones allowed to access satellite imagery. Statement D: No one should have access to satellite imagery. Which statement do you agree with the most? ○ Statement A ○ Statement B ○ Statement C ○ Statement D

Why do you agree the most with the statement that you chose? If you cannot articulate a reason, please enter "Uncertain". Text box _______

Below is an image of people standing, at varying image qualities. Suppose a commercial satellite took images of you from this angle. Select the most detailed image quality you are comfortable with being publicly available. ○ [Image of people in parking lot downsampled to 1m resolution] ○ [Image of people in parking lot downsampled to 50cm resolution] ○ [Image of people in parking lot downsampled to 15cm resolution] ○ [Image of people in parking lot downsampled to 5cm resolution] ○ [Image of people in parking lot downsampled to 1cm resolution]

Consider the most detailed image quality you chose from the previous question. What is the most frequent you would be comfortable with a satellite of that image quality taking pictures of you? ○ Never ○ Every year ○ Every month ○ Every week ○ Every day ○ Every hour ○ Every minute ○ Every second

[Attention Check] For this survey, it is important that you read the instructions carefully to ensure the results are accurate. If you are reading these instructions, please type 10 into the answer box below. [Image shown similar to Figure 3 but this time of 8 people] _______

[Demographics] Almost done! This final page contains some demographic questions.

In which state do you currently reside? [Drop-down of all 50 states, Washington D.C., and Puerto Rico]

Which of these best describes your current gender identity? ○ Man ○ Woman ○ Non-binary/third gender ○ Other ○ Prefer not to say

Choose one or more races that you consider yourself to be ○ White or Caucasian ○ Black or African American ○ American Indian/Native American or Alaska Native ○ Asian ○ Native Hawaiian or Pacific Islander ○ Other ○ Prefer not to say

How old are you? ○ Under 18 ○ 18-24 years old ○ 25-34 years old ○ 35-44 years old ○ 45-54 years old ○ 55-64 years old ○ 65+ years old ○ Prefer not to say

What is your present religion, if any? ○ Protestant ○ Roman catholic ○ Mormon ○ Orthodox (such as Greek or Russian Orthodox) ○ Jewish ○ Muslim ○ Buddhist ○ Hindu ○ Atheist ○ Agnostic ○ Something else ○ Nothing in particular ○ Prefer not to say

Generally speaking, do you usually think of yourself as a Republican, a Democrat, an Independent, or something else? ○ Republican ○ Democrat ○ Independent ○ Other [Text box]_______ ○ No preference ○ Prefer not to say

[End of Survey] [Message showing MTurk code]

Thank you for taking this survey! If you want to learn about current satellite capabilities and use cases, here is a webpage for one of the many commercial satellite companies: https://www.planet.com

B SURVEY CODEBOOK

These themes are based on all free response questions in the survey. The benefits and harms section of the codebook are from the questions in results Section 6.2. The access considerations section summarizes responses to the scenario questions (Section 6.3) and statement questions (Section 6.5). The adversaries/untrusted parties category combine free responses from all questions.

B.1 Potential Benefits

- Mapping
- Real Estate and Infrastructure
- Government accountability
- Legal Compliance and Crime Detection
- Targeted Advertising
- Emergency Response
- Studying Natural Phenomena
- More Information
- Surveillance
- Agriculture

B.2 Potential Harms

- Invasion of privacy
- Security
- Facilitating Crimes
- Military Operations
- Surveillance
- Law enforcement Abuse
- Natural Resource Misuse
- Unwanted Advertising
- Incorrect Identification
- Compliance
- AI Integrations

B.3 Access considerations

This list includes any factors respondents mentioned when they explained why to give/not give access to satellite imagery.

- Adversaries
- Technical Logistics
- Personal utility
- Conditional access
- Social benefit
- Privacy expectations
- Legality
- Fairness/ethics
- Innovation
- Slippery slope
- Preventing abuse
- More knowledge
- Public safety

B.4 Adversaries/Untrusted Parties

This includes any group respondents specifically mentioned that they didn't want to give access to satellite imagery or that they didn't trust to not misuse the satellite imagery.

- United States government
- Other world governments
- The public
- Stalkers
- Exes
- Law enforcement
- Employers
- Insurance companies

C PRIVATE ACTIVITY IMAGE METRICS CODEBOOK

See Figure 4 for how we grouped image metrics based on privacy concerns that people brought up. The codebook is represented in a graph (tree) format. The concerns people brought up fell under 5 high-level categories: cars, text, pets, equipment, and people (these are five child nodes under a root "entity" node in the tree). Within the people category, we included a sub-category of movement (a child node). Within each category were aspects of images that would need to be observable in order to distinguish a particular activity that was deemed private by at least one person during the brainstorming session.

Each child node requires equal to or more resolution than its parent node metric. For example, knowing what clothes someone is wearing requires a better spatial resolution than knowing that a person is in the image. For another example, in the people node, the most specific movement to measure based off the brainstorming sessions is the finger position. The people movement branch of the tree could be used to predict activity type, such as running if the body position is known, and if the finger position is known, it could be used to predict as specific as finger swiping patterns on a phone.

D SPATIOTEMPORAL RESOLUTION COMFORT

See Figure 5.

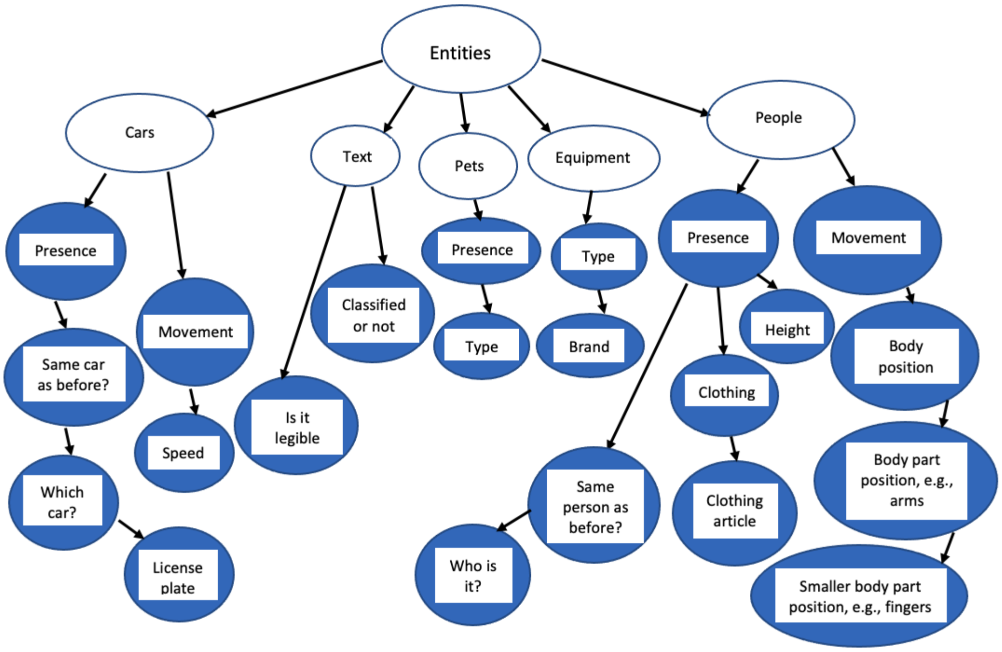

Figure 4: Summary of private activity image metrics. Nodes that are not shaded are categories that are not themselves observable metrics. Shaded nodes are image metrics.

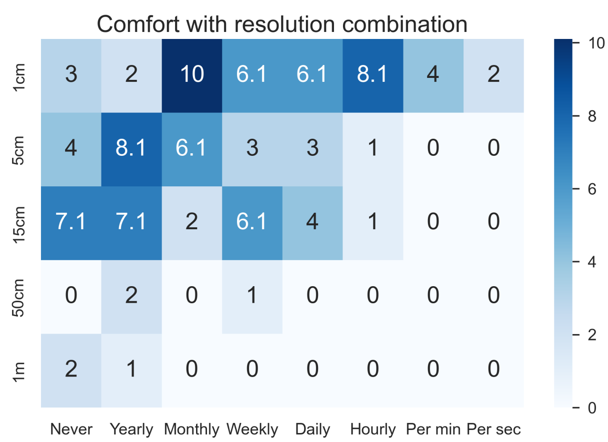

Figure 5: Percentages of respondents who are comfortable with the given spatial and temporal resolution combinations. The most common choice was allowing 1cm spatial resolution satellite images to be taken monthly of themselves.