



NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

REPURPOSE OF IN-ORBIT STORAGE

METEOROLOGICAL SATELLITES (A FIFTY-DAY STUDY)

by

Timothy Sands

June 2023

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Periodically, environmental monitoring satellites are moved into on-orbit storage to await a call to duty. With a contract cost for four satellites of \$1.4 billion, alternatives to storage are investigated and suggested in this study. Assuming a readership unfamiliar with the civilian satellite program, significant elaboration of program details is presented in a mild brief review of the literature, extracting the current state-of-the art novel suggestions. Next, novel utilizations are proposed. Eight novel applications are found in the literature: Oil palm mapping, cloud mapping, cloud property and atmospheric state estimation, hurricane prediction and analysis, surface urban heat island, Earth-distribution of solar radiation, fire location and burning area estimation, hail-producing storm detection. Five novel applications are proposed: Bio-radar, stereo winds, imager re-calibration using GOES-R, nuclear detonation detection, and communications relay.				
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ABSTRACT

Periodically, environmental monitoring satellites are moved into on-orbit storage to await a call to duty. Considering typical contract costs for four satellites of roughly \$1.4 billion, alternatives to storage are investigated and suggested in this study. Assuming a readership unfamiliar with the civilian satellite program, significant elaboration of program details is presented in a brief review of the literature, extracting the current state-of-the art suggestions for potential applications. Next, utilizations are proposed. Eight innovative applications are found in the literature: Oil palm mapping; cloud mapping; cloud property and atmospheric state estimation; hurricane prediction and analysis; surface urban heat island; Earth–distribution of solar radiation; fire location and burning area estimation; and hail-producing storm detection. Five novel applications are proposed: Bio–radar; stereo winds; imager re-calibration using GOES-R; nuclear detonation detection; and communications relay.

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I. INTRODUCTION

The purpose of this manuscript is to introduce readers presumed unfamiliar with GOES satellites displayed in Figure 1 and ponder the question of how the military might utilize several available GOES systems.

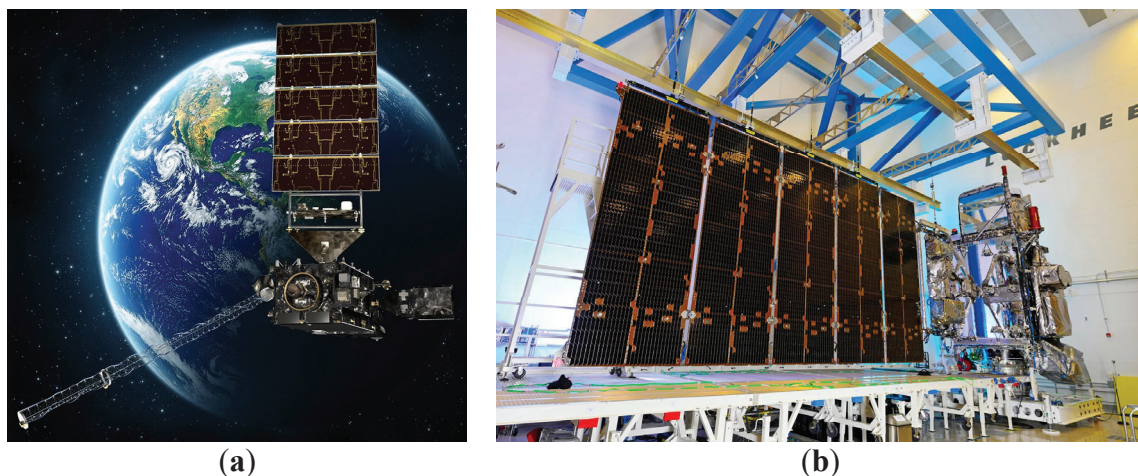


Figure 1. Geostationary Operational Environmental Satellites (GOES)
(a) Arguably, one of the most advanced weather satellites ever developed by the U.S. national oceanographic and atmospheric administration was positioned as “GOES-East” in Fall 2017, moving to 75 degrees west over the equator, becoming operational in November[[1]]. (b) GOES-18 in a clean room [[2]]. Images used consistent with NASA policy: “NASA content (images, videos, and audios) are generally not copyrighted and may be used for educational or informational purposes without needing explicit permissions” [[3]].

GOES–14, an operational environmental geostationary orbiting satellite depicted in Figure 2 was placed into storage on-orbit in 2009 to await a future call to duty [[4]]. Upon the launch of GOES–18 depicted in **Error! Reference source not found.**(b), GOES–17 was also destined for storage on-orbit [[2]]. Meanwhile, GOES–13 has already been transferred to the military. GOES–14,15,17 could be transferred to the military as well, since they all reside in storage on-orbit[[5]].

The GOES system specializes in sensing the environment, providing imaging data processing and dissemination; acquisition and monitoring of the space environment; and space weather measurement near the Earth. The system also provides collection of data, including: reception, interrogation, and relay of data from Earth to data-acquisition-and-command stations; and then also provides broadcast of environmental sensor data, using the product distribution and access (PDA) and the rebroadcast service (GRB).

Distress signals are relayed to the search and rescue satellite-aided tracking system (SARSAT) from marine vessels or aircraft. Weather data is continuously relayed to the weather information network of the emergency managers (EMWIN), while civil emergency managers receive relays of other meteorological data[[6]].

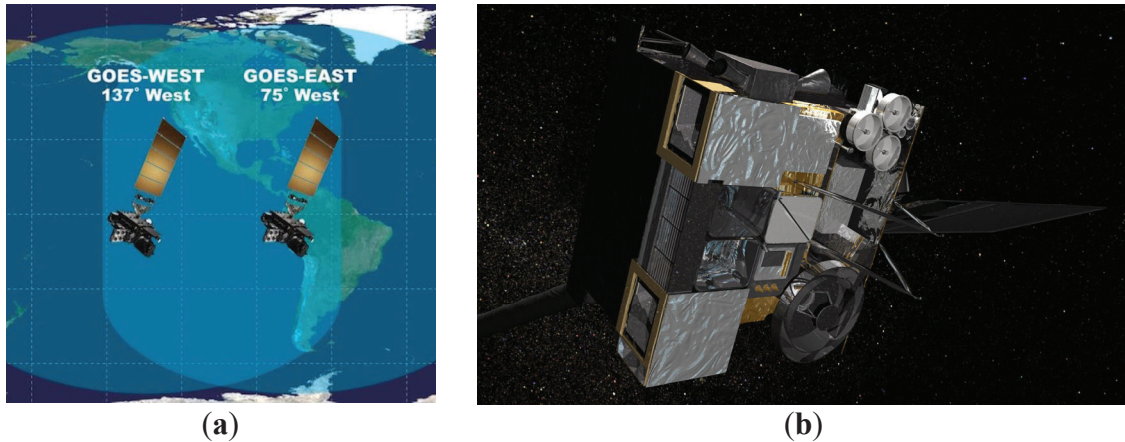


Figure 2. Orbital positions and on-orbit storage
(a) the GOES-East orbital position, GOES-16 coverage is comparable to GOES-West. (b) GOES-14, the satellite being moved to on-orbit storage with an anticipation of deploying to replace either GOES-West or GOES-East [[4]]. Images used consistent with NASA policy: “NASA content (images, videos, and audios) are generally not copyrighted and may be used for educational or informational purposes without needing explicit permissions” [[3]].

To aid readability of the manuscript, definitions of acronyms, variable, and terms are provided periodically in **Error! Reference source not found.**Table 8, which are placed proximal to the usage of the verbiage.

The Materials and Methods section of this manuscript introduces the GOES system and subsystems, including payloads, after foremost offering a brief review of the literature from which suggested novel uses are summarized. Afterwards, novel proposals are offered beyond those found in the literature review.

A. LITERATURE REVIEW

Cloud cover, particularly over tropical regions, challenge the management and planning of agriculture in the creation of maps depicting distributions of oil palm. Remote sensing of oil palm from other crops seems to be feasible but proves difficult, using only satellites sensing in optical wavelengths. Seeking to ameliorate the difficulties, reference [[7]] used the Google Earth Engine to evaluate the combination of open-source data from microwave and optical satellites, particularly by evaluating a test site, using the

combination of L-band, C-band and topographic images from various satellites (e.g., Landsat 8, PALSAR-2, Sentinel-1, 2). Land-use maps with 95%–97% accuracies were achieved, using a combination of images from Sentinel–1 and Sentinel–2, while combining images from PALSAR–2 and Landsat 8 achieved accuracies of 96%–100%. Combining L–band images proved inferior to combining C–band images for radar palm oil estimation, where the area was underestimated in the former case of L–band images. Geostationary Operational Environmental Satellite 13 (GOES–13) imagery for four months in each year, 2014–2017, were compared against Aqua and Terra satellite (cloud) products and measurements from aircraft (in situ). Favorable comparison of regression modeling seemed to indicate the potential amelioration of three-dimensional biases in studies of relative illumination and cloud spatial inhomogeneity. Enhanced reflectance shadowing correlated with overestimation and underestimation in the forward hemisphere (backscatter) [[8]]. Enhanced cloud property measurements (high spatiotemporal resolution cloud properties, including cloud water path) are provided by the advanced baseline imager on (for example) the GOES–16 satellite. Improved weather forecasting is possible, using adaptively thinned observations of cloud water path, necessitating merely 40% of the normal data volume [[9]].

Term	Description
GOES–East 1	GOES-16 Sector view of tropical Atlantic - blue portion of the spectrum
GOES–West 2	GOES-17 Sector view of Pacific USA - red portion of the spectrum
Landsat 8	NASA and the U.S. Geological Survey Earth observation mission
PALSAR–2	Synthetic Aperture Radar (SAR) aboard LOS-2
Sentinel–1, 2	European space agency Earth observation missions
GOES–16	First spacecraft to carry a lightning mapper in geostationary orbit.
GOES–14	Known as GOES-O prior to reaching its operational orbit
GOES–R	Renamed GOES–16
L-band	Radio frequencies from 40 to 60 GHz
C-band	Radio frequencies from 2.4GHz to 5GHz

¹ Such tables are offered throughout the manuscript to aid readability.

Table 1. Table of proximal variable and acronym definitions.¹

Hurricane analysis and prediction generally use satellite data for model validation by verifying model forecasts, where radiative transfer models may be used to generate synthetic images from state variables in forecasts. Verification includes wind strengths; gale radii; intensity biases and errors; and tracker biases and errors. Brightness in infrared images from GOES–R (GOES–16) have been used to create synthetic images that were

used to verify vortex size, asymmetric structure, and intensity, while application to tropical cyclone Dorian resulted in weaker forecast intensity, small vortex size prediction, but also higher speed wind and larger eye predictions. The use of satellite data nonetheless provided global coverage of real-time, high-resolution data [10].

Dynamic prediction of surface urban heating to characterize energy balance at the ground is complicated by urban area heterogeneity. Use of satellite observations of land temperature can enhance urban surface energy balance, e.g., GOES images have recently been applied to New York City [[11]]. A new method (called spatial downscaling) to combine high *temporal* resolution GOES images with the fine *spatial* resolution images of Landsat-8 illustrates improved spatial errors, imaging the city's built-up areas and tree canopy covered lands. Meanwhile, the so-called heliostat method may be used to estimate cloud cover by attenuation of solar radiation, and the method seems to overestimate cloud cover compared to a standard average annual map of solar radiation [[12]]. GOES satellite data may also be used to model gamma function distributions or tapered power law with exponents (whose value is less than two), indicating a small number of large flares constitute the total flare population energy. Interestingly, the energy distribution curve of stellar flare energy does not overlap with the curve of solar flare energy [[13]].

Particularly since fire data measured on the ground has limited temporal availability, GOES advanced baseline imager proves effective to provide real-time forecasting in addition to burn area estimating (using an ensemble approach), for daily fire tracking and emissions-modeling [[14]]. Historically, hail-producing storm monitoring used snapshots of satellite data, while using a constant flow of multispectral GOES data can highlight convective initiation and also decrease brightness temperature (with time) associated with cooler values than the tropopause related to updraft (slight) weakening with small sized ice crystals just prior to the report of hail [[15]].

The advanced baseline imager seems preeminent in research using GOES satellite data. Nonetheless, many other sources of data are available, and this manuscript elaborates such. After reiterating the extracted state-of-the-art benchmarks from the literature review and briefly listing the novelties to be presented, Section 2's materials and methods details the available systems on the satellite, while Section 3's results postulate some novel applications.

B. STATE OF THE ART BENCHMARKS

The following list highlights the current state-of-the-art, interesting, proposed utilizations found in the literature review:

1. Oil palm mapping
2. Cloud mapping
3. Cloud property and atmospheric state estimation
4. Hurricane prediction and analysis
5. Surface urban heat island
6. Earth–distribution of solar radiation
7. Fire location and burning area estimation
8. Hail-producing storm detection

C. NOVELTIES PROPOSED

The following list includes novel thoughts for future uses of in–orbit (formerly) civilian meteorological satellites:

1. Bio–radar
2. Stereo–winds
3. Imager re-calibration using GOES-R
4. Nuclear detonation detection
5. Communications relay

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II. MATERIALS AND METHODS

Satellites are often used to monitor and understand land, the atmospheric oceans, and climate dynamics, in addition to providing space weather data. Operated by the national oceanic and atmospheric administration (NOAA), the geostationary operational environmental satellites (GOES) are designed, procured, and manufactured by the United States' national air and space administration (NASA). Articulated in this section of the manuscript is a detailed description of systems available on the GOES satellites, including their basic operational features, hinting at novel applications.

Acronym/variable	Definition
GOES	Geostationary operational environmental satellites
NOAA	National oceanic and atmospheric administration
NASA	National air and space administration
GOES(R)-17	The second in the four-satellite series (GOES-16, -17, -T, and -U)
SAR-SAT	Search and rescue satellite-aided tracking system

¹ Such tables are offered throughout the manuscript to aid readability.

Table 2. Table of proximal variable and acronym definitions¹

1. Geostationary Operational Environmental Satellite (GOES)

There are three major functions of the GOES(R)-17 (also known as GOES-West) spacecraft: environmental sensing, data collection, and data broadcast [[6]].

2. Environmental sensing

Environmental sensing includes near-Earth space measurement of weather; and processing, acquisition, and dissemination of data for imaging and (space) environment monitoring. Furthermore, environmental sensing comprises six key instrument systems that are further elaborated in section II.A. amongst several other useful systems: 1) The advanced baseline imager; 2) the geostationary lightning mapper; 3) the extreme ultraviolet and x-ray irradiance sensors; 4) the magnetometer; 5) the space environment in-situ suite; and the 6) solar ultraviolet imager.

3. Data collection

Data collection involves receiving surface-based earthly data, interrogation, and data relay to ground stations. The data collection major function is performed by the data collection system and search and rescue.

4. Data broadcast

The data broadcast function relays marine vessel and aircraft distress signals to the search and rescue satellite-aided tracking system (SAR-SAT). This function ensures the emergency manager's weather information network receives weather facsimile and meteorological data. The data broadcast function comprises a) the advanced weather interactive processing system; b) the comprehensive large array-data stewardship system; c) the emergency managers weather information network; d) the GOES rebroadcast; e) the high-rate information transmission; f) the product distribution and access; and g) the search and rescue satellite aided tracking system.

A. GOES PAYLOAD KEY SUBSYSTEMS

This subsection of the manuscript articulates at least a dozen key payload systems, while the subsequent subsection describes four highly relevant spacecraft subsystems. The key payloads include the imager; image navigation and registration; advanced baseline imager; solar x-ray imager; solar ultraviolet imager; space environment monitor; space environment in-situ suite; extreme ultraviolet and x-ray irradiance sensors; the sounder and the energetic particle sensors. The four key spacecraft subsystems include the communications subsystem; the communications payload; telemetry, command, and control; command data & handling; and guidance, navigation, and control. The sounder and image instruments perform the main mission of GOES [[16]].

1. GOES imager

The imager is a very highly sensitive receiver whose advanced capabilities are a focus for potential novel applications. **Error! Reference source not found.** and **Error! Reference source not found.** highlight both capabilities and spectra to be a focus of the recommended results in Section III. Signals at the emphasized wavelengths and frequencies are available for suggested, future usages.

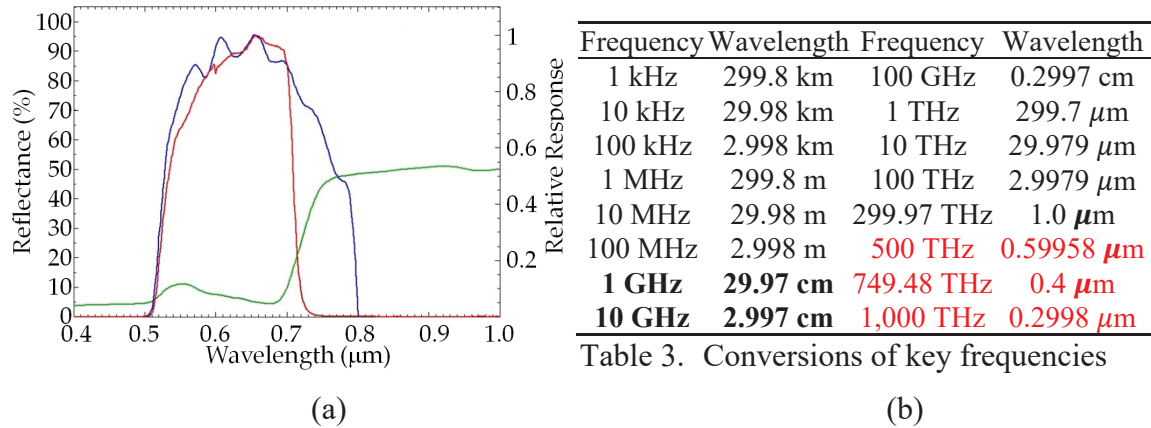


Figure 3. Typical GOES imager data and frequency conversion
 Images and data [17] are used consistent with NASA policy: “NASA content (images, videos, and audios) are generally not copyrighted and may be used for educational or informational purposes without needing explicit permissions” [[3]].

A radiometer is used by GOES for (multi-spectral) imaging in five-channels, sensing thermal energy and solar energy reflected from the Earth’s atmosphere and surface. Data from the imager can be used to ascertain water vapor, cloud height and temperature, cloud cover, and surface temperature. Sample data depicted in **Error! Reference source not found.** from the imager depicted in **Error! Reference source not found.** is include with full-earth imagery including the earth’s edge with local regions monitored continuously for wind determination and phenomena on the mesoscale. The location and size of scanned areas may be defined using a single pixel, selectable to comply with commands from the ground, where all the (spectral) channels are co-registered with each other spatially. Star-sensing to enhance positioning measurement is aided by the detector array (in the visible spectrum). Figure 4 (a) displayed the focal plane array assembly mated to the loop hear pipe with radiator mating atop the condenser plate. The Earth is imaged onto the (blue rectangle) the center which is the charge–couple device. Ground handling uses the red frame. The geostationary lightning mapper sensor is displayed in Figure 4 (b) being prepared for thermal vacuum testing, permitting an interior view, since the lens assembly is visible with the exterior baffle removed (the upper part of the photo), while the hexapod is visible (in the lower part of the photo) [6].

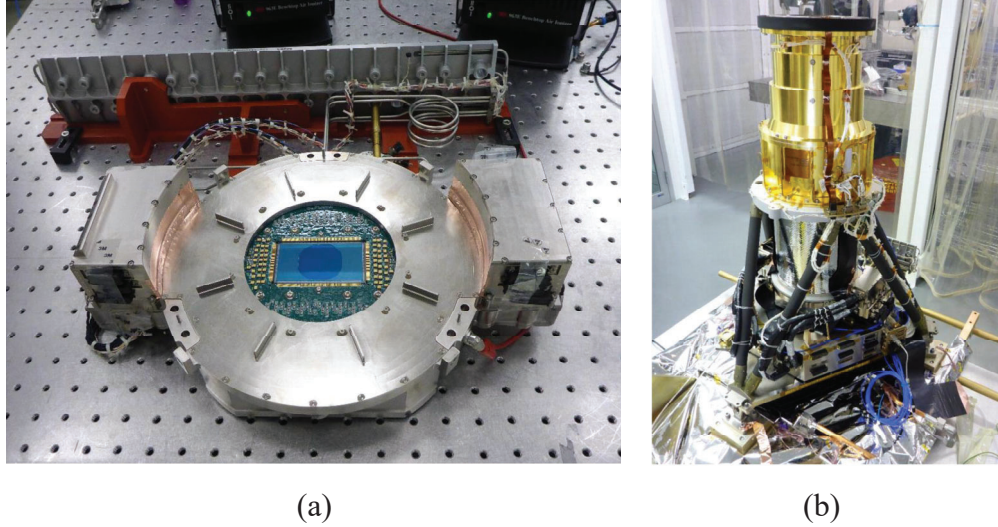


Figure 4. Focal plane imaging details and geostationary lightning mapper
 Images used consistent with NASA policy, “NASA content (images, videos, and audios) are generally not copyrighted and may be used for educational or informational purposes without needing explicit permissions” [[3]]

2. GOES image navigation and registration

Using the primary instrument and communications system to sense star locations, and geographical landmarks, the methodology of image navigation and registration (INR) is used to maintain location accuracy with daily information on locations in a coordinate system defined in fixed-earth coordinates without ground interpolation [[16]].

3. GOES advanced baseline imager



Figure 5. GOES Imager
 Images used consistent with NASA policy, “NASA content (images, videos, and audios) are generally not copyrighted and may be used for educational or informational purposes without needing explicit permissions” [[3]]

The advanced baseline imager (ABI) depicted in **Error! Reference source not found.** is the GOES-R primary instrument with sixteen spectral bands for viewing weather, the

environment, and oceans. Meanwhile only ten infrared bands are used by the older GOES spacecraft plus two visible channels and four near-infrared channels [[17]]. The advanced baseline imager is depicted in Figure 5 (a), where Figure 5 (b) displays on the left the electronics unit (EU), while visible on the right is the sensor unit (SU) [6].

Acronym/ variable	Definition
INR	Image navigation and registration
ABI	Advanced baseline imager
GOES	Geostationary operational environmental satellite
GOES-R	Program of 4 most advanced geostationary weather satellites: GOES-R/S/T/U

Table 4. Table of proximal variable and acronym definitions.

4. GOES solar x-ray imager

Geosynchronous orbits allow direct line-of-sight solar observations on all days and at all times, except for when GOES nears equinox each day for up to an hour entering the shadow of the Earth. Normally, images are collected each minute with optimized sequencing for three-phenomena observations of solar flares, active regions, and structures of the coronal (reference Figure 6 in [[24]]).

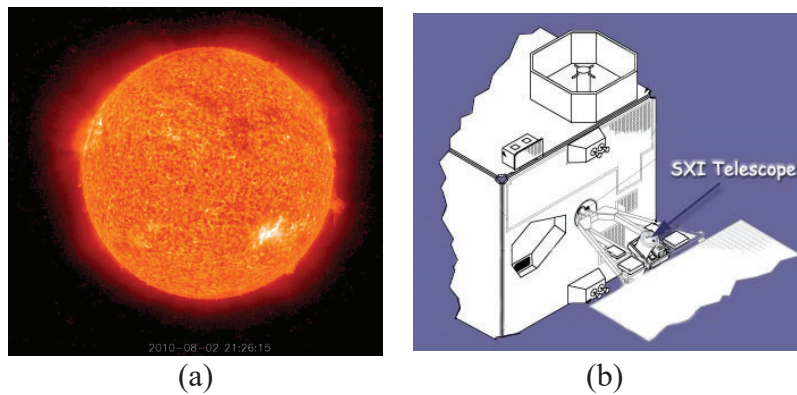


Figure 6. Solar x-ray image and imager

Images used consistent with NASA policy, “NASA content (images, videos, and audios) are generally not copyrighted and may be used for educational or informational purposes without needing explicit permissions” [[3]] Images used consistent with NASA policy, “NASA content (images, videos, and audios) are generally not copyrighted and may be used for educational or informational purposes without needing explicit permissions” [[3]].

Launched in 2001 on GOES-12, the solar x-ray imager provides almost uninterrupted, continuous frame rate, soft x-ray images of the solar full disc. Between 0.6–6.0 nanometers, temperature discrimination with ten arcsecond resolution on five arcsecond pixels is provided by metallic thin-film filters [[25]]. Figure 6 (a) displays a solar x-ray imager capture of a solar storm on August 1, 2010 [22]; while Figure 6 (b)

includes a telescope image of the solar x-ray imager instrument on GOES-12 [23] Table 1. Table of proximal variable and acronym definitions.

Acronym/ variable	Definition
SXI	Solar x-ray imager
GOES-12	Known as GOES-M before becoming operational launched in 2001
NASA	National Aeronautics and Space Administration
EXIS	Extreme ultraviolet and x-ray irradiance sensors on GOES-R Series
EXEB	Extreme ultraviolet sensor/x-ray sensor electrical box

Table 5. Table of proximal variable and acronym definitions.

5. GOES solar ultraviolet imager

Lockheed Martin produces the solar x-ray imager, which provides coronal mass and solar flare early detection by monitoring solar x-rays, warning humans in high-altitudes and low-earth orbits, and providing opportunities to activate protective actions for communications satellites. Subfigure (a) of Figure 7 contains a photograph of the solar x-ray imager in the flight software facility, while subfigure (b) depicts a schematic front aperture assembly (door mechanism, filter mechanism, and solar position sensor), as well as extreme ultraviolet sensor electric box, and x-ray sensor [6].

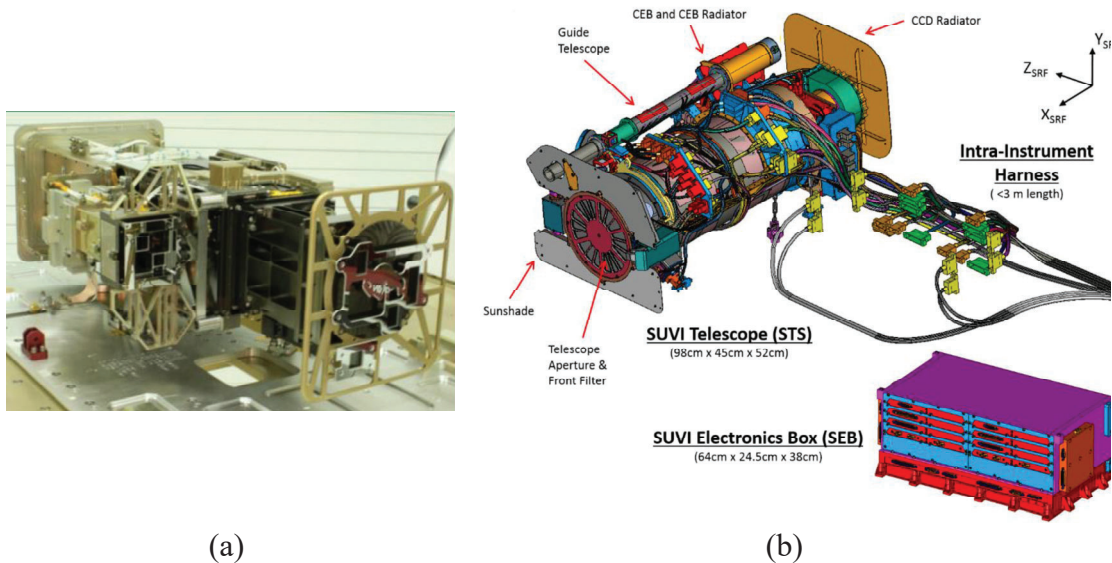


Figure 7. Solar ultraviolet imager
 (a) Photograph in the flight software facility of front aperture assembly (door mechanism, filter mechanism, and solar position sensor), as well as extreme ultraviolet sensor electric box, and x-ray sensor; (b) The solar ultraviolet imager instrument; [[6]] Images used consistent with NASA policy: “NASA content (images, videos, and audios) are generally not copyrighted and may be used for educational or informational purposes without needing explicit permissions” [[3]].

Amongst the instruments built by Assurance Technology Corporation (formerly Panametrics Inc.) is a data collection system used to relay data to users (e.g., rain gauges, river heights, tide sensors and user stations like ships and weather stations), including particle emissions (alpha particles, solar protons, and electrons) and extreme ultraviolet emissions [[16]].

6. GOES space environment monitor

Instruments for space environment monitoring are also built by Assurance Technology Corporation and include a magnetometer [[16]].

7. GOES sounder

Together with the imager, the sounder performs the system's primary missions and includes production of vertical atmospheric moisture and temperature profiles, ozone distribution, cloud top and surface temperatures and is used to produce long-range and medium-range weather forecasts [[16]].

8. GOES energetic particle sensors

Essentially identical sensors of energetic particles (energetic electron, proton, and alpha particles) reside on GOES 8–12 and 15 [[19]]. Two of three detector assemblies focus on protons in the 0.8–500 mega electron volt energy range, and alpha particles in the range 4–400 mega electron volts, while one channel measures electrons greater than 500 kilo electron volts. Alpha particles (above 640 mega electron volts per nucleon) and high energy protons (above 370 mega electron volts) are monitored by the third detector [[20]]. Two channels measure the flux of electrons (whose energy is greater than two mega electron volts) and protons whose energy is between roughly one-half and four mega electron volts. Additionally solar event detection is possible using an electron detector for protons whose energy exceeds 80 mega electron volts. Lastly, one mega electron volt is the cutoff of geomagnetic energy in geostationary orbits, so detection may be realized by fusing the information of the lower channel energies of trapped protons and protons from events outside the magnetosphere [[21]].

9. GOES magnetometers

Magnetic fields may be decomposed into three components sometimes expressed as angle of dip, the horizontal component of the earth's magnetic field and magnetic

inclination, or magnetic declination. The Earth's magnetic field near spacecraft in the magnetosphere and ionosphere is measured by the magnetometer [[16]].

10. GOES geostationary lightning mapper

The first operational, geostationary orbiting lightning mapper was the GOES geostationary lightning mapper (GLM), which can continuously detect both cloud-to-ground and in-cloud lightning over the land and oceans of the Americas and surroundings. Increasingly, early warnings of tornadoes and severe thunderstorms may be provided when lightning mapping data is enhanced with ground measurement and data from the advanced baseline imager [[17]].

B. GOES SPACECRAFT KEY SUBSYSTEMS

Some basic spacecraft subsystems are described in the following subsections, including the communications subsystem; communications payload; and telemetry, command, and control subsystem.

1. GOES communications subsystem

Emergency communications is another GOES mission, where satellites transmit data to a ground station in Wallops Island, Virginia, and where it is afterwards relayed to the operations center in Suitland, Maryland, where information is processed and distributed world-wide. The spacecraft also has a transponder dedicated to detection of distress calls in the form of emergency locator transmissions associated with search and rescue beacons [[16]].

Mission data transmission and **communications relay services** are provided by many transponder payloads referred to by several names, including the data collection system, the raw data link system, the GOES rebroadcast, the high-rate information transmission/emergency managers weather information network, and the search and rescue satellite-aided tracking system. Dual polarized X-band uplinks are used for the GOES rebroadcast transponders with dual polarized L-band earth coverage downlink. Utilizing S-band uplink and L-band downlink, a narrow bandwidth transponder is used by the high-rate information transmission/emergency managers weather information network. Meanwhile, UHF uplinks are used for the search and rescue and data collection platform report services with narrow bandwidth L-band downlinks. S-band uplink is used for the

data collection platform command service, while UHF downlinks are used with a narrow band transponder. The tracking, telemetry, and control subsystem provides support from orbit raising to normal on-station operations, using communications service functions including:

- Tracking, telemetry, and control for orbit raising using S-band communications;
- Housekeeping command and data acquisition for on-orbit command, telemetry and tracking using S-band and L-band;
- Data collection platform links are used for both oceanographic and terrestrial support;
- Relaying imaging data, the weather information network of the emergency managers (EMWIN) broadcast, and the high-rate information transmission signal;
- Distress messages from the search and rescue emergency locator transmitters and emergency position indicating radio beacons; and
- Using the GOES rebroadcast service data link to rebroadcast sensor data.

The national oceanographic and atmospheric administration satellite operations facility is used for mission phases that launch and raise orbits (e.g., deployments, apogee thruster firings, and post-separation acquisition), and the facility is supported by a network of stations across the globe to fulfill requirements for command, telemetry, and tracking.

2. GOES communications payload

The communications payload detects distress signals and provides repeater transponders and antennas for data services, including

1. processed data relay;
2. weather facsimile low-rate information transmission;
3. search-and-rescue;
4. data collection platform;
5. data collection platform interrogates;
6. emergency manager's weather information network relay; and
7. the sounder sensor data and multiuse data link onboard data transmit services.

In addition to a UHF cup dipole antenna, two antennas are included on the common structure, one each for the S and L bands in addition to another two for the L-band. The downlink for search and rescue uses one of the antennas in the L-band, while both the search and rescue and data collection platform use the antenna in the UHF.

Meanwhile, the S–band uplink and the downlink transmissions of the multiuse data link; the data collection platform; the weather facsimile/low-rate information transmission; the sounder sensor data; the processed data relay; and the emergency managers weather information network relay all share the S/L–band antenna. Multiple services are accommodated by using multiplexers with antennas in the L–band, the UHF, and the S/L–bands. An amplifier in the S–band receiver is used for data collection platform interrogates; weather facsimile/low-rate information transmission; processed data relay; and emergency managers weather information network relay; and a processor is used for both the UHF search and rescue and data collection platform, as well as the UHF uplink signal. The digital data passed from the imager/sounder and instrument remote telemetry and command units and from the multiuse data link share a common modulator unit.

Solid state amplifiers raise the downlinks of data from the search and rescue/data collection platform, S–band receiver data, and data from the multiuse data link/sounder sensor to the necessary level for transmission. Full redundancy is achieved for all active hardware, by cross strapping the coaxial switches and passive power splitter/combiners [[16]].

Term	Definition	Term	Definition
PDR	Processed data relay	SAR	Search and rescue
MDL	Multiuse data link	SD	Sounder sensor data
EMWIN	Emergency managers weather information network relay	SOCC	Satellite ops control center
WEFAX/LRIT	Weather facsimile/low-rate information transmission	T&C	Telemetry and command
NASA	National air and space administration	CDA	Command & data acquisition
NOAA	National oceanographic and atmospheric administration	RF	Radio frequency
DCPI	Data collection platform interrogate	DCPR	Data collection platform

Table 6. Table of proximal variable and acronym definitions.¹

3. GOES telemetry and command (telemetry, command, and control)

The functional command and control interface between ground and spacecraft is provided by the “N–P telemetry and command system,” comprising baseband and radio frequency segments.

The command and data acquisition station receives downlinks and forwards (to the satellite operations control center configuration) health and spacecraft and payload status. The telemetry and command (T&C) subsystem manage expendables and controls mission operations, using a radio frequency (RF) segment, comprising two transponders, interconnecting microwave devices, and three antennas facilitating operations without

interference. A digital segment includes an internally redundant pyrotechnic squib driver unit and distributed, redundant units that interface with a station in Wallops, Virginia, operated by the national oceanographic and atmospheric administration (NOAA), while the deep space network operated by the national air and space administration serves as a backup, and also serves as the primary ground station for launch and orbit-raising ground station. The deep space network stations in Wallops and in the Indian Ocean are used to interface with the ground centers when raising satellite orbits [[16]].

4. Guidance, navigation, and control

Two star-trackers and one inertial measurement unit provide attitude control for GOES-R satellites (GOES-16/GOES-East), whose subsystems include the redundancy of three star-trackers and three inertial measurement units. Two accelerometers and four hemispheric resonating gyros comprise each inertial measurement unit. Attitude tracking from any unknown initial condition is provided by a wide field-of-view star tracker up to twenty-times per second. Operationally, positioning is provided by the global positioning system (GPS), while the guidance, navigation, and control system also includes analog sun sensors, which are particularly useful for contingency operations [[17]].

Attitude control of the GOES-13 (GOES-N) is provided by reaction wheels, star trackers, sun sensors, earth sensors, redundant microprocessors, an x-ray positioner, and a solar array drive [[16]].

Subsystem	Description	Host	Subsystem	Description	Host
PAYLOAD					
Imager	Imager	GOES 14	SEM	Space environment monitor	GOES 14
Imager	Imager	GOES 15	SEISS	Space environment I-situ suite	GOES 17
INR	Image navigation and registration	GOES 14	EXIS	EUV and x-ray irradiance sensors	GOES 17
ABI	Advanced baseline imager	GOES 17	Sounder	Sounder	GOES 15
SXI	Solar x-ray imager	GOES 14	Sounder	Sounder	GOES 14
SXI	Solar x-ray imager	GOES 15	EPS	Energetic particle sensor	GOES 15
SUVI	Solar ultraviolet imager	GOES 17	Magnet	Magnetometers	GOES 15
XRS	X-ray imager	GOES 15	MAG	Magnetometer	GOES 17
HEPAD	High energy proton & alpha detector	GOES 15	GLM	Geostationary lightning mapper	GOES 17
SPACECRAFT					
Comm	Communications subsystem	GOES 14	TC&C	Telemetry, command, and control	GOES 15
Comm	Communications payload	GOES 15	CD&H	Command data & handling	GOES 17
Comm	Communications payloads	GOES 17	GNC	Guidance, navigation, and control	GOES 17
TANDC	Telemetry and command	GOES 14			

Table 7. Key subsystems on GOES 14, 15, and 17

Translational motion is provided by a hypergolic, bipropellant propulsion system, using nitrogen tetroxide (oxidizer) and monomethyl hydrazine (fuel). Four regulated pressure helium tanks are also available for propulsion, where independent valves distribute propellant selectively [16].

Available subsystems on GOES systems are summarized in Table 7, which are also elaborated on in the appendix. With a lengthy elaboration of the available satellites and their available systems and subsystems in Section II, Section III, the appendix elaborates on requisite details for considering potential novel uses for repurposing the satellites.

III. RESULTS

Having firstly extracted novel applications suggested in the most recent literature, and then having elaborated on details of the satellites and their systems and subsystems, this section expresses innovative thinking about how to repurpose the satellites for new missions. These missions suggested include bio-radar, three-satellite stereo winds, providing reference for recalibration of older satellite imager channels, nuclear detonation detection, and utilization of the communications capabilities of the satellites.

A. BIO-RADAR

According to Alec Eden, in [[26]], the Doppler effect was initially offered in 1842 in [[27]] describing how motion imparts frequency phase shifts that may be measured to infer the properties of constituent motion. In 2017, a new bio-radar was illustrated to read heartrates from a distance, without physical contact with the subject. [[29]] Bio-radar uses this principle to characterize the rise and fall of a person’s chest to estimate rates of respiration. Search and rescue missions may be enhanced by short-range applications, while long-range applications may be used to detect living (respiring) things, even in noisy environments. To overcome patient movements, short-range applications using continuous wave signals at a C-band frequency of 5.8 gigahertz (5.2-centimeter wavelength) have successfully been developed, where such movements and other clutter are assumed to be random. Band designations are summarized in **Error! Reference source not found.**, which should be compared to the sample data display in **Error! Reference source not found.**’s display of imager data spectra, eliminating consideration of the GOES imager, which operates in the C-band. Direct *active* transmissions are unavailable in GOES systems to facilitate bio-radar.

Band	Frequencies	Band	Frequencies
UHF	300–3000 MHz	K-band	12–40 GHz
L-band	1–2 GHz	Q-band	40–50 GHz
S-band	2–4 GHz	V-band	50–80 GHz
C-band	4–8 GHz	W-band	80–90 GHz
X-band	8–12 GHz		

¹ Within K-band, spacecraft may operate communications, radio science, or radar equipment at Ku-band about 15 to 17 GHz and Ka-band around 20 to 30 GHz.

Table 8. Standard band designations¹

Nonetheless, a bio-radar capability was even used to detect emotions from a distance, where detected vital signs were validated to identify happiness, fear, and a neutral emotion state in subjects. This capability seems to hold relatively longer-term promise, following future technical developments in signal processing. As a reminder, the GOES spacecraft TT&C system transmits in the S-band and L-band (2–4 GHz). As frequency increases, less coverage but faster data transmission speeds results. Table 8 includes the standard band designations, revealing the difference between and GOES systems and the cited bio-radar frequency. Future research should evaluate the efficacy of C-band for *semi-active* bio-radar potential, where collaborative active transmitters are combined with the global coverage of GOES receivers.

B. A DEMONSTRATION OF THREE-SATELLITE STEREO WINDS

Wind direction and height may be obtained by tracking clouds from multiple directions, referred to as stereo winds. Single satellite measurements do not directly measure height; instead, the height is inferred from brightness temperatures in the infrared. Stereo coverage of two satellites with intersecting fields of view can be augmented by a third spacecraft to produce coverage of a full hemisphere. Carr et al. [[30]] just proposed taking advantage of the advanced baseline imager’s five-hundred-meter resolution on GOES–18 to augment the utilization of the pair of GOES–16 and GOES–17. Consistency between the three satellites’ data was elaborated for fusion of the disparate sensor data, and the claimed results included a “nearly” full hemispherical view. Comparing the fused results to observed data illustrated estimated winds were accurate to one-hundred millimeters per second with altitude accuracy of one-hundred seventy-five meters [[30]]. This nascent capability hints at the availability of real-time wind estimation over an entire hemisphere of the globe.

C. USING GOES-R ABI FULL-DISK REFLECTANCE AS A CALIBRATION SOURCE FOR OLDER GOES IMAGER VISIBLE CHANNELS

Especially since the key variables of climate reside in visible channels, an interesting notion is to address the lack of onboard calibration capabilities of older imagers in geostationary orbits by using newly orbited channels of solar reflectance. Reference [[31]] evaluated the use of GOES–16,17 advanced baseline imager data for visible channel calibration of GOES–8–13 sensors. The applied method defines a calibration target used

with older sensor data, taking advantage of the integrated full-disk reflectance stability to generate new, stable equations of calibration that are consistent with former techniques, and implementation is possible by operational agencies as opposed to engineering/acquisitions agencies.

D. NUCLEAR DETONATION DETECTION

Vela satellites from Los Alamos National Laboratory depicted in **Error! Reference source not found.** had eighteen gamma and internal neutron detectors in addition to a dozen external detectors of x-rays powered by simple ninety-Watt solar panels, while late versions (e.g., Vela 6) were capable of correlating x-ray and gamma ray bursts.

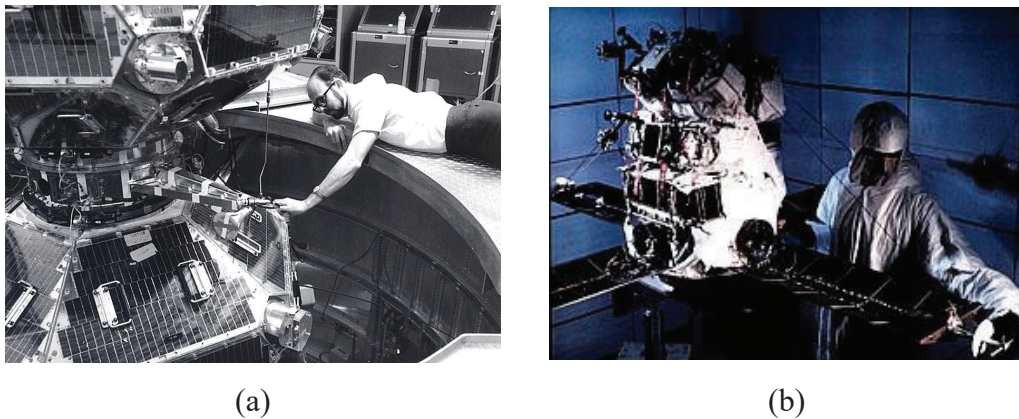


Figure 8. Los Alamos National Laboratory satellites
(a) Vela satellite used for nuclear treaty verification [[31]]. (b) ALEXIS satellite. Images used consistent with LLNL image-use policy [[32]]

Extreme ultraviolet sensor (EUV) detection of nuclear events was validated in 1993 in the space mission Array of Low Energy X-ray Imaging Sensors (ALEXIS) depicted in **Error! Reference source not found.** GOES utility for characterizing gamma and x-ray events seem applicable to nuclear detonation detection, since having such sensors in orbit hint at untapped utility for nuclear detonation detection.

E. COMMUNICATIONS RELAY

The communications services interfaces of GOES-R are displayed in Figure 9 and Figure 10, where Figure 9 depicts the raw data links, while Figure 10 displays the bent pipe services.

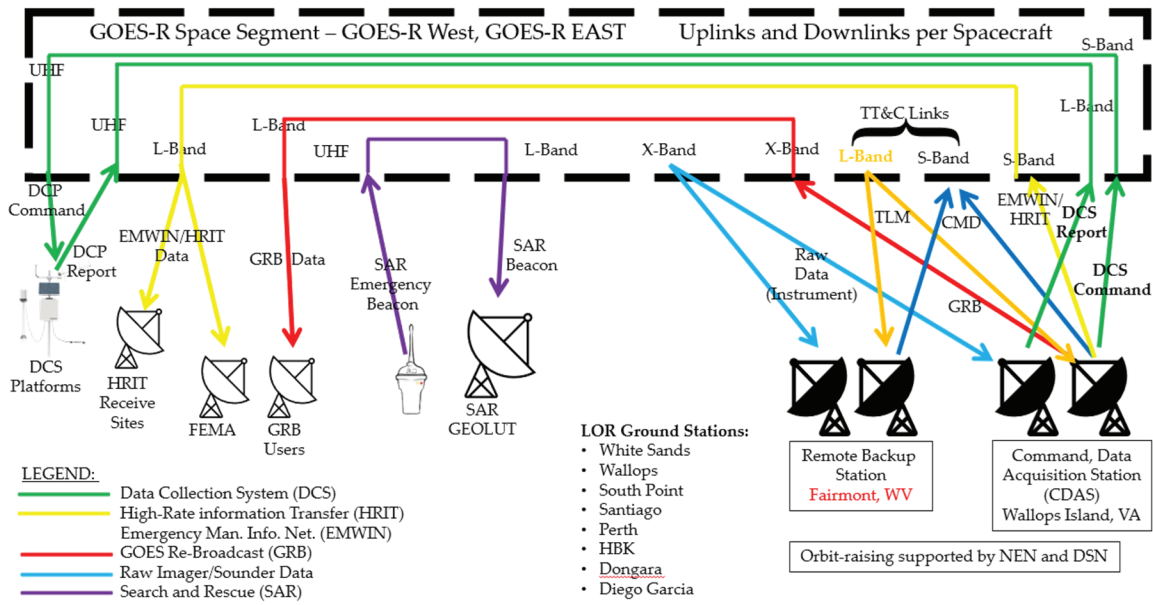


Figure 9. Communications links overview.

The image is a modified, recreated version of a Figure 9-1 in [18]. Images used consistent with NASA policy: “NASA content (images, videos, and audios) are generally not copyrighted and may be used for educational or informational purposes without needing explicit permissions” [3]

Environmental data dissemination and acquisition is part of the geostationary orbiting GOES-R (GOES-16) system’s mission, where dissemination is performed by the communications subsystem via the following functions:

- Instrument data transmission to the command and data acquisition stations
- Signal relays of payload services in support of:
 - Rebroadcast of the GOES signals
 - Broadcasts of the emergency manager’s weather information network
 - Search and rescue
 - Data collection platforms
- Global positioning system navigation signal reception
- Deep space network stations’ & command and data acquisition stations’ two-way ranging and doppler
- Spacecraft telemetry transmission to command and data acquisition stations

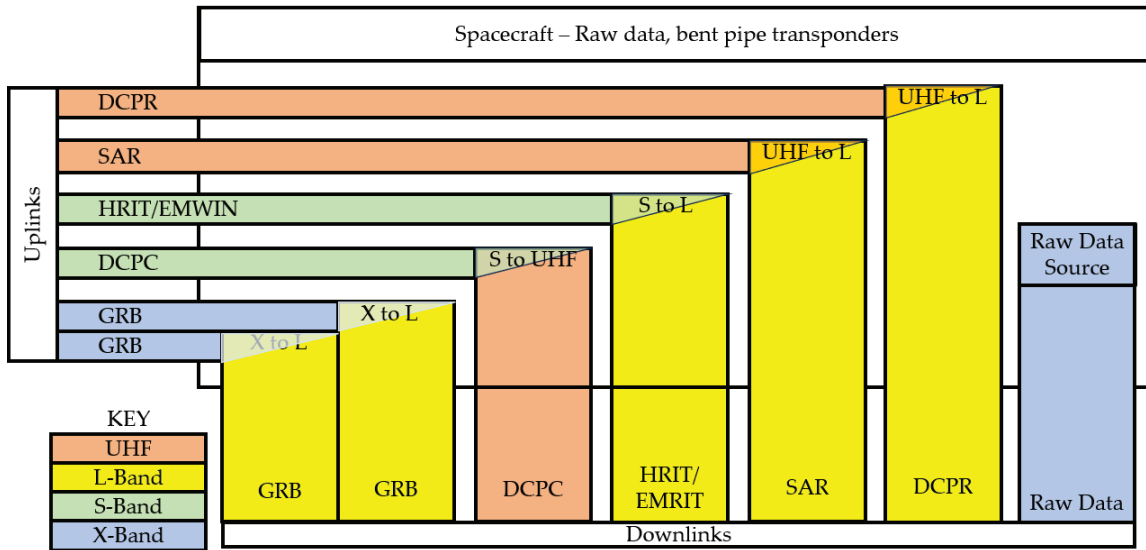


Figure 10. GOES bent-pipe transponders by frequency band.
 The image is a recreated version of a Figure 9–2 in [18]. Images used consistent with NASA policy: “NASA content (images, videos, and audios) are generally not copyrighted and may be used for educational or informational purposes without needing explicit permissions” [3].

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IV. DISCUSSION

Eight novel applications are found in the literature: Oil palm mapping; cloud mapping; cloud property and atmospheric state estimation; hurricane prediction and analysis; surface urban heat island; Earth–distribution of solar radiation; fire location; burning area estimation; and hail-producing storm detection. Five novel applications are proposed: Bio–radar; stereo–winds; imager re-calibration using GOES-R; nuclear detonation detection; and communications relay. The final four recommendations seem immediately implementable, while the first proposal necessitates future research to enhance the range of bio–radar to benefit search and rescue operations.

A. STATE OF THE ART BENCHMARKS

The following list highlights the current state of the art:

1. Oil palm mapping
2. Cloud mapping
3. Cloud property and atmospheric state estimation
4. Hurricane prediction and analysis
5. Surface urban heat island
6. Earth–distribution of solar radiation
7. Fire location and burning area estimation
8. Hail-producing storm detection

B. NOVELTIES PROPOSED

The following list includes novel thoughts for future purposes of in–orbit meteorological satellites:

1. Bio–radar
2. Stereo winds
3. Imager re-calibration using GOES-R
4. Nuclear detonation detection
5. Communications relay

C. RECOMMENDED FUTURE RESEARCH

To enhance global search and rescue missions, future research should evaluate the efficacy of C–band for semi–active bio–radar potential, where collaborative active transmitters are combined with the global coverage of GOES receivers.

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APPENDIX A

Subsystem	Description	Status ¹	Frequencies
PAYLOAD			
Imager	Imager	Green	1694.1 MHz ² VNIR bands: Band 1: 470nm, Band 2: 640 nm, Band 3: 865 nm, Band 5: 1610 nm and Band 6: 2250 nm MWIR bands: Band 7: 3900 nm and Band 11: 8500 nm LWIR bands: Band 13: 10350nm, Band 14: 11200nm, Band 15: 12300nm and Band 16: 13300nm
INR	Advanced Baseline Image (ABI) Image navigation and registration ³	Green	0.5-to-4 and 1-to-8 Angström wavelength bands 18 infrared bands from 3.7 to 14.7 micrometers, as well as one visible band
SEM	Space environment monitor	Green	14.71 Åm, 14.37 Åm, 14.06 Åm, 13.64 Åm, 13.37 Åm, 12.66 Åm, 12.02 Åm; 11.03 Åm, 9.71 Åm, 7.43 Åm, 7.02 Åm, 6.51 Åm, 4.57 Åm, 4.52 Åm, 4.45 Åm, 4.13 Åm, 3.98 Åm, 3.74 Åm; 0.70 Åm
Sounder	Sounder	Green	1-8 Angstrom (0.1-0.8 nm) and 0.5-4.0 Angstrom (0.05-0.4 nm)
SXI	Solar x-ray imager	Green	
SPACECRAFT			
ACS	Attitude control system	Green	
Comm	Communications subsystem	Green	
Power	Electrical power subsystem	Green	
Prop	Propulsion	Green	
TANDC	Telemetry and command	Green	
Thermal	Thermal control system	Green	

¹ Color coding used by program office [[5]].

² [36]

³ [37]

Table 9. Subsystem status, GOES 14

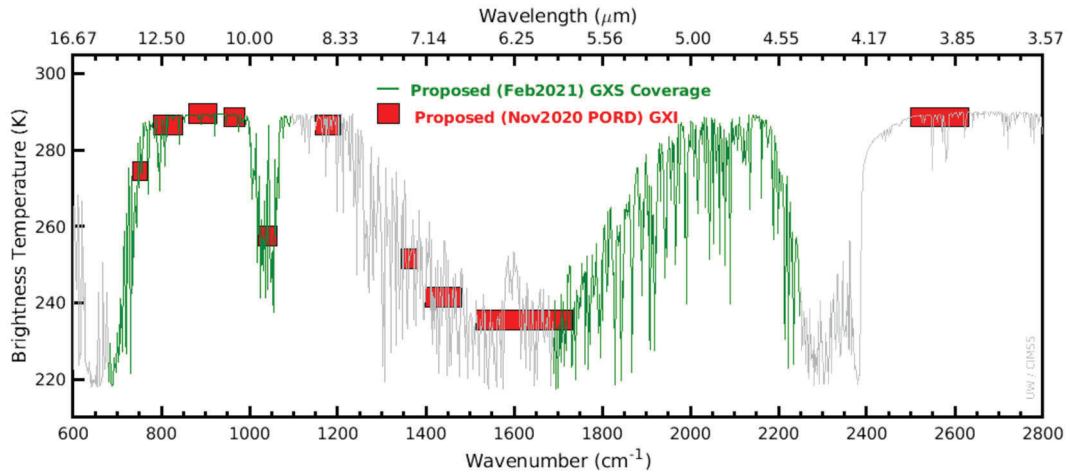


Figure 11. Instrument coverage

The green highlights show the electromagnetic spectrum that the GXS would observe. Image credit: UW/CIMSS [35]. Images used consistent with NASA policy: “NASA content (images, videos, and audios) are generally not copyrighted and may be used for educational or informational purposes without needing explicit permissions” [[3]].

Subsystem	Description	Status ¹
COOLOG	Cooler outgas heater	Green
Electronics	Imager electronics	Green
IR Bias	IR detector bias	Green
PATCH	Patch configuration	Green
PWRSUP	Imager power supply	Green
SCAN MOTOR	Scan motor	Green
VISIBLE PREAMP	Visible preamp system	Green

¹ Color coding used by program office [[5]].

Table 10. GOES 14 Imager subsystem status.

Subsystem	Description	Status ¹
DMC	Dynamic motion compensation status	Green
IMC	Image motion compensation status	Green

¹ Color coding used by program office [[5]].

Table 11. GOES 14 Image navigation and registration subsystem status.

Subsystem	Description	Status ¹
EPS	Energetic particle sensor	Green
HEPAD	High energy proton and alpha detector	Green
MAGNETOMETER 1	Magnetometer #1	Green
MAGNETOMETER 2	Magnetometer #2	Green
XRS EUV	X-ray sensor/extreme ultraviolet sensor	Green

¹ Color coding used by program office [[5]].

Table 12. GOES 14 Space environment measure subsystem status.

Subsystem	Description	Status ¹
COOLOG	Cooler outgas heater	Green
ELECTRONICS	Sounder electronics	Green
FILTER WHEEL	Sounder filter wheel	Green
IR BIAS	IR detector bias	Green
PATCH	Patch configuration	Green
PWRSUP	Sounder power supply	Green
SCAN MOTOR	Scan motor	Green

¹ Color coding used by program office [[5]].

Table 13. GOES 14 Sounder subsystem status.

Subsystem	Description	Status ¹
CCD	Charge-coupled device sensor	Green
ELECTRONICS	Data electronics box (DEB) status	Green

¹ Color coding used by program office [[5]].

Table 14. GOES 14 Solar x-ray imager subsystem status.

Subsystem	Description	Status ¹
PAYLOAD		
EPS	Energetic particle sensor	Green
HEPAD	High energy proton and alpha detector	Blue
Imager	Imager	Blue
Magnet	Magnetometers	Green
Sounder	Sounder	Yellow/Blue
SXI	Solar x-ray imager	Blue
XRS	X-ray imager	Yellow/Blue
SPACECRAFT		
A&OB	Attitude and orbit control	Green
Comm	Communications payload	Blue
Power	Electrical power	Yellow/Blue
FIC	Fuel for inclination control	Green
Mech	Mechanisms	Green
Prop	Propulsion	Green
TC&C	Telemetry, command, and control	Green
Thermal	Thermal control system	Green

¹ Color coding used by program office [[5]].

Table 15. Subsystem status, GOES 15.

Subsystem	Description	Status ¹
PAYLOAD		
ABI	Advanced baseline imager	Yellow
SEISS	Space environment I-situ suite	Green
SUVI	Solar ultraviolet imager	Green
EXIS	EUV and x-ray irradiance sensors	Green
MAG	Magnetometer	Green

GLM	Geostationary lightning mapper	Green
SPACECRAFT		
CD&H	Command data & handling	Green
GNC	Guidance, navigation, and control	Green
EPS	Electrical power subsystem	Green
Propulsion	Propulsion	Green
Mechanisms	Mechanisms	Green
Thermal	Thermal control	Green
Communications	Communications payloads	Green

¹ Color coding used by program office [[5]].

Table 16. Subsystem status, GOES 17.

Frequency	Wavelength	Frequency	Wavelength
1 kHz	299.8 km	50 MHz	5.995 m
2 kHz	149.9 km	100 MHz	2.998 m
5 kHz	59.96 km	200 MHz	1.499 m
10 kHz	29.98 km	2500 MHz	0.5995 m
20 kHz	14.99 km	1 GHz	29.97 cm
50 kHz	5.996 km	2 GHz	14.99 cm
100 kHz	2.998 km	5 GHz	5.997 cm
200 kHz	1499 m	10 GHz	2.997 cm
500 kHz	599.5 m	20 GHz	1.499 cm
1 MHz	299.8 m	50 GHz	0.5997 cm
2 MHz	149.9 m	100 GHz	0.2997 cm
5 MHz	59.95 m	200 GHz	0.1499 cm
10 MHz	29.98 m	500 GHz	0.05997 cm
20 MHz	14.99 m	1 THz	0.02997 cm

Table 17. Frequency wavelength conversions.

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