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Current and future use of the band 13.25-13.75 GHz by spaceborne active sensors

RS Series

Remote sensing systems

International Telecommunication Union

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REPORT ITU-R RS.2068-2

Current and future use of the band 13.25-13.75 GHz by spaceborne active sensors

(2006-2013-2021)

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1 Introduction and background

1.1 Introduction

The purpose of this Report is to document current and future use of the 13.25-13.75 GHz band, Earth exploration-satellite service (EESS) (active), by spaceborne active sensors. This Report includes bandwidth requirements of spaceborne active sensors, scientific feasibility of performing the same measurements in bands other than the 13.25-13.75 GHz band, and the continuous need for EESS (active) sensors to operate in the 13.25-13.75 GHz band. These uses and requirements are addressed from the viewpoint of the three major instrument types that make use of the band:

– scatterometers;
– altimeters;
– precipitation radars.

1.2 Background

The World Radiocommunication Conference 2003 (WRC-03) made many changes to the allocations in the 13.75-14 GHz band. Prior to WRC-97, several frequency bands were allocated on a secondary basis to the EESS and the space research service for use by radiolocation stations (i.e. spaceborne active sensors) installed on spacecraft. One of these bands was the 13.4-14 GHz band. WRC-97 decided to allocate the 13.25-13.75 GHz band to the EESS (active) and space research (active) services on a primary basis as a result of the various allocation decisions taken at the Conference regarding active sensors. However, WRC-97 also saw the need to maintain the previous secondary allocation in the 13.75-14 GHz portion of the band for use by several active sensor instruments that were currently in orbit or were planned and built as their characteristics could not be changed. These provisions were set forth in the Radio Regulations with termination dates of 1 January 2000 and 1 January 2001 for various active sensor instruments. At this time, all the EESS (active) sensors that were deployed in the 13.75-14 GHz frequency range have completed their missions and are no longer operating in that frequency band. In addition, WRC-15 decided to add the fixed-satellite service (space-to-Earth) allocation for Region 1 to the 13.4-13.65 GHz frequency band. The characteristics for the EESS (active) sensors are contained in Recommendation ITU-R RS.2105.

2 Scatterometers

2.1 Use of the 13.25-13.75 GHz band by scatterometers

Scatterometers are types of radar devices that measure the near surface vector winds over the oceans. Wind data are critical to the determination of regional weather patterns and global climate. No other instrument can provide all weather measurements of the global vector winds.

Good capability for acquisition of weather data exists over land, but not over the oceans where our only knowledge of surface winds comes from infrequent, and sometimes inaccurate, reports from ships. Since approximately two-thirds of the Earth's surface is covered by oceans, data from scatterometers plays a key role in understanding and predicting complex global weather patterns, ocean circulation, and climate systems. In support of ongoing climate change studies, it is required to maintain the continuity of measurements taken by scatterometers in the 13.25-13.75 GHz band.

Two scatterometers that were developed in the United States of America are the NSCAT (NASA scatterometer) that was launched in 1996 on Japan's Advanced Earth Observing Satellite (ADEOS) and the SeaWinds scatterometer, which was launched in 1999 on NASA's Quick Scatterometer (QuikSCAT) satellite, which operated until 2018, and in 2002 on Japan's ADEOS-II satellite as part of the Earth Observing System (EOS). NSCAT was designed to operate at a centre frequency of 13.995 GHz and operated until 1997. SeaWinds is a derivative of NSCAT and uses many of the same components, however the centre frequency was changed to 13.4 GHz to fit within the then new 13.25-13.75 MHz allocation. A scatterometer that was developed in China was launched in 2011 on HY-2A NGSO ocean satellite. The scatterometer was designed to operate at a centre frequency of 13.256 GHz. The SCAT instrument on CFOSAT (CNES/CNSA) and OSCAT instruments on ISRO's ScatSAT and OceanSat series also use the 13.25-13.75 GHz frequency band.

2.2 Bandwidth requirements

Existing scatterometer designs in the 13.25-13.75 GHz band use either a fixed frequency, unmodulated pulse or a spread spectrum frequency-modulated pulse to probe the sea surface. The transmitted frequency spectrum for the fixed frequency pulse is narrow due to the low pulse repetition rate (62 Hz) and large pulse width (5 ms). Present scatterometers use spread spectrum modulation in order to obtain more precise definition of the surface cell where wind measurements are being taken, the required radio-frequency bandwidth is 5 MHz.

Future spaceborne rotating pencil-beam and rotating fan-beam scatterometers are typically expected to use bandwidths much greater than 5 MHz up to 100 MHz to improve measurements through the use of alternative modulation techniques. Simulations have shown that for higher wind speed, wider bandwidth provides a larger number of samples for each of the data resolution cells and results in better performance; for lower wind speed, narrower bandwidth can lead to better signal to noise of the measured backscattering power.

2.3 Feasibility of using other bands

Scatterometer measurements and the derived knowledge about wind vectors are based on microwave scattering effects over water-surface capillary waves. Measurements at wavelengths comparable to that of the capillary waves caused by water-surface wind interaction is necessary in order to achieve the sensitivity required to measure wind speeds and directions for winds having velocities as low as 3 m/s. Measurements of winds with such velocity are needed to satisfy the requirements for determination of variation in weather and climate. The wavelength of frequencies within the band 13.25-13.75 GHz is commensurate with the dimensions of the capillary waves produced by low speed winds with the result that the scatterometer is highly sensitive to local winds, especially at low wind speeds. At the same time, a scatterometer operating in the band 13.25-13.75 GHz exhibits low sensitivity to non-wind effects such as swells and surface film/surface tension.

Possible alternative bands to the 13.25-13.75 GHz band have been considered. The two bands closest to 13.5 GHz that are currently available to the EESS (active) are the 9.3-9.9 GHz and 17.2-17.3 GHz bands. Neither the 9.3-9.9 GHz band nor the 17.2-17.3 GHz band is as desirable for use by scatterometers as the 13.25-13.75 GHz band. This is a consequence of not having a large collection of data on radar scattering from the ocean surface at frequencies other than near 13.5 GHz where the SeaSat scatterometer operated and 5.3 GHz where the ERS-1 scatterometer operated. Operating a scatterometer in a band other than those near 13.5 GHz or 5.3 GHz will require re-examining the processing that relates the radar return to the wind speed and direction. The processing developed for the 5.3 GHz band required a number of aircraft and tower experiments before launch and more than six months of refinements after the launch of ERS-1. Developing a new process will result in an interruption of the data flow to the science community for the period that is required to gain confidence in the new algorithm. A frequency change would also result in some loss of the continuity of the long-term data set the consequences of which are unknown.

Scatterometers operating in the band 13.25-13.75 GHz have higher sensitivity to low wind speeds than scatterometers operating near 5.3 GHz. It is believed that scatterometer operation in the band 9.3-9.9 GHz would also exhibit lower sensitivity than operation in the band 13.25-13.75 GHz. The low speed wind vectors are important to the studies of the variability of ocean currents. At frequencies above the band 13.25-13.75 GHz, atmospheric attenuation due to water content (e.g. cloud cover and rain) becomes more variable. In the band 17.2-17.3 GHz, it may be possible to operate a wind scatterometer; however, operating in this frequency band would result in degraded performance since the scatterometer would be more sensitive to atmospheric water content and surface film/surface tension effects. At frequencies above 20 GHz, the variability of the atmospheric attenuation would render the instrument useless without employing other means of simultaneously measuring the atmospheric variability.

Another factor that makes continued use of the 13.25-13.75 GHz band important for scatterometry is the large amount of data that has been acquired at these frequencies since the inception of these measurements in 1996. The SeaSat scatterometer and the NASA aircraft scatterometer both operated in this frequency band as well as the NSCAT instrument. Continued use of this band for future scatterometers will allow more meaningful cross-comparison of data sets acquired in the future with those from the past. A broader database acquired by instruments operating with similar parameters can be expected to produce a more accurate long-term scientific model.

A dual-frequency scatterometer called WindRadar onboard FY-3E NGSO meteorological satellite is under development in China. Considering the advantage of using the near 13.5 GHz and 5.3 GHz bands simultaneously, this radar uses these two frequency bands to achieve ocean vector winds under almost all-weather and all wind speed conditions.

2.4 Long-term need for operation in the 13.25-13.75 GHz band for scatterometers

The long-term requirement to operate spaceborne scatterometers in the 13.25-13.75 GHz band is to derive wind speed and wind direction. These data products will continue to be incorporated in climate studies and models used for weather prediction and ocean circulation, which are all key factors in the understanding of the environment. As discussed above, only the 13.25-13.75 GHz band can support the required measurement sensitivity for the scatterometers. In addition, a database acquired over a period of more than 20 years only exists in this band. This unique historical database enhances the value of future scatterometer data interpretation.

The NSCAT scatterometer was constructed to operate at 13.995 GHz. Protection of NSCAT operations until the year 2000 was ensured by a regulatory provision, which was suppressed by WRC-03. On the other hand, the SeaWinds scatterometer was only in a developmental stage at the time of WRC-97 and its centre frequency was changed to 13.4 GHz in order to avoid frequency-sharing constraints with respect to the fixed-satellite service in the 13.75-14 GHz band. It is projected that a 100 MHz bandwidth will be needed for future scatterometers in order to improve measurements through the use of alternative modulation techniques.

3 Altimeters

3.1 Use of the 13.25-13.75 GHz band for altimeters

A spaceborne radar altimeter is a downward-looking pulsed-radar system mounted on an orbiting spacecraft. Up to recently, they were primarily ocean remote sensing instruments, but there is now interest in the tracking data that they acquire over land and ice surfaces, as implemented on the European Remote Sensing (ERS) satellite altimeters. Radar altimeter missions, such as Synthetic Aperture Radar (SAR) Radar Altimeter (SRAL) on SENTINEL-3 mission, are now acquiring topography data and meeting requirements for sensing over all types of surfaces (sea, coastal areas, sea ice, ice sheets, ice margins and in-land waters).

Altimeters are used to measure range from the satellite to the targeted surface. This very precise height measurement, when combined with very precise orbit determination and corrections for other media effects, provides very accurate global maps of the Earth's surface topography, in particular over oceans. The location, speed, sea temperature and direction of ocean currents worldwide can be deduced from this knowledge of ocean topography. This provides an understanding of ocean circulation and its time variability that is crucial to understanding the Earth's climate change. Altimeter data can also provide measurements of surface-significant wave height (ocean waves) and backscatter at nadir from which wind speed (but not the wind vector) can be determined. In addition to ocean surface monitoring, satellite-altimeter radars also exhibited strong capabilities to monitor a wide variety of in-land water surfaces and measure their elevation. The excellent accuracy of the height measurements enables the survey of terrestrial snow-covered regions, survey of the ice-sheets surface elevation, the estimation of their mass balance and the recovery of pertinent geophysical parameters such as snow pack characteristics and surface roughness. The meteorological forecasting community is interested in the above measurements from all operational altimeter systems.

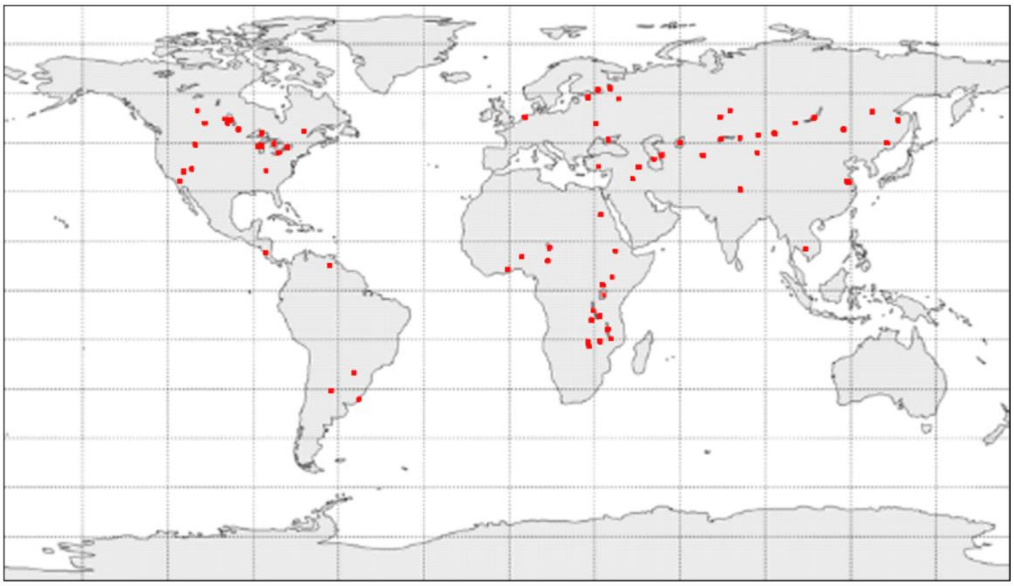
The spaceborne radar altimeters currently operating in the 13.25-13.75 GHz band are JASON-3, CryoSat-2, SENTINEL-3, GEO-IK-2 and HY-2A. The JASON-1 satellite was decommissioned on 1 July 2013. The JASON-2 mission ended operations in October 2019. Their successor JASON-3 provides continuity of service to users of the JASON-1 and JASON-2 mission data. The JASON-CS (JASON-Continuity of Service, SENTINEL-6, launched in 2020) carries a radar altimeter package designed to continue the high precision altimetry missions of JASON-2 and JASON-3. The CryoSat-2 carries an instrument SAR/Interferometric Radar Altimeter (SIRAL) which operates at 13.575 GHz. The ENVISAT mission ended operations in April 2012 and was replaced by the new radar altimeter SRAL which flies on board SENTINEL-3 (launched in 2016). The first generation of GEO-IK-2 altimeter uses 13.74 GHz frequency. Second generation of this system uses 13.575 GHz frequency that allows in the future to use the increased bandwidth of 500 MHz. The HY-2 series (CAST/NSOAS) carry radar altimeters. JAXA plans to launch a radar altimeter on the COMPIRA mission and CNES/CNSA plan to launch one (SWIM) on the CFOSAT follow-on. A radar altimeter is on the SWOT (NASA/CNES) mission to be launched in 2021. The CRISTAL mission, scheduled by ESA for launch by 2027, will also carry a radar altimeter at 13.5 GHz. Radar altimeters are now an operational tool for earth/ocean/air sciences and, as such, will continue to be launched and used long into the future.

As an example of the use of altimeters over inland bodies of water, the United States Department of Agriculture (USDA) currently obtains global measurements, using the JASON series of sensors, of 83 global reservoirs, lakes, wetland regions, and river channels. The data obtained and the precise measurement areas for each reservoir and lake is publicly available at: https://ipad.fas.usda.gov/cropexplorer/global_reservoir/.

Figure 1 provides a depiction of the 83 global points (red dots) monitored in the USDA programme.

FIGURE 1

USDA global reservoir and lake monitoring program



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The band 13.25-13.75 GHz was chosen long ago based on considerations such as the need for an allocation for radars on spacecraft, a wide allocated bandwidth to satisfy science objectives, hardware availability and compatibility with the allocated radiolocation service. The first spaceborne altimeter to use this band was the Skylab S-193 experiment in the early 1970s. Since then, there have been many altimeters using this band (e.g. GEOS-C, Skylab, GEOSAT, TOPEX-POSEIDON, JASON-1, JASON-2, JASON-3, ERS-1, ERS-2, ENVISAT, CryoSat, SENTINEL-3, GEO-IK-2 and HY-2A). This use represents a considerable investment in hardware design, hardware development, mission operations, data reduction, software design, scientific analysis, modelling and database construction.

A very large database has been obtained from these altimeters that allow the proper interpretation of current and future altimeter data. These data are very sensitive to the frequencies used for their collection. A change in operating frequency could negate the applicability of a substantial amount of that existing database. Also, a significant amount of hardware for both inflight use and ground use has been developed in both the United States of America and in Europe that will support future missions. Much of this hardware is designed to operate within the 13.25-13.75 GHz band. Based on the above, the need for altimeters working within this frequency band will extend well into the future. As an example, it should be noted that the SRAL altimeter will operate on multiple satellites through at least 2025 with the likelihood of additional follow-on missions.

3.2 Bandwidth requirements

The bandwidth employed by current JASON altimeters is 320 MHz. ERS-2 and ENVISAT employed 330 MHz and 360 MHz respectively, while the SRAL altimeters on board SENTINEL-3 employ a bandwidth of 350 MHz. As in any radar system, the precision of the altimeter’s height (range) measurement is dependent on the bandwidth used. The JASON altimeter uses pulse compression (chirp full de-ramp stretch) to achieve its fine precision. In JASON, the 320 MHz allows for an effective compressed pulse width of 3.125 ns (46.5 cm basic resolution) before further processing and averaging is done. Ultimately, the precision on the channel in the 13.25-13.75 GHz band is less than 3 cm.

Several studies have been carried out in the ITU-R that examined the need to extend the bandwidth for altimeters to as much as 500 MHz. These studies examined other effects on the accuracy of height measurement including electromagnetic bias, sea-state bias, ionospheric effect, tropospheric effect and orbit determination. Previously, it was considered that these effects were large enough to dominate the error budget for the height measurement. Recent work during the development of current instruments (such as SRAL on SENTINEL-3) have demonstrated that the impact of these effects on the error budget can now be improved and currently allow to improve the overall accuracy below 1 cm in certain modes.

Therefore, it is expected that the reduction of systematic errors through improvements in modelling, instrument design, etc., will allow future instruments to efficiently make use of increased bandwidth to as much as 500 MHz to further improve their precision. Also, components for altimeters with such wide bandwidths are becoming much more available and affordable. Overall, altimeters operating in the Ku band and having bandwidths larger than 500 MHz cannot currently be accommodated because of the bandwidth of the primary allocated band.

There are also potential changes to the basic design of altimeters that may produce a need for wider bandwidths: multibeam altimeters, scanning altimeters, and synthetic aperture altimeters fall into this category. Another design that would require a wider bandwidth is for an altimeter that would decorrelate its along-track measurement by use of frequency agility or frequency hopping.

Another reason that bandwidths up to 500 MHz will be needed is to accommodate both an altimeter and a scatterometer on the same spacecraft without overlapping their emissions.

Based on the results of WRC-97, an allocated bandwidth of 500 MHz is available since the lower limit of the band allocated for active sensors was extended downward from 13.4 GHz to 13.25 GHz. It is agreed that the current 500 MHz allocation can accommodate both present and potential future needs for spaceborne altimeters near 13.5 GHz.

The CRISTAL mission, planned for launch in 2027, will operate an altimeter with a 500 MHz bandwidth, which will allow it to meet the mission's stringent range resolution requirements.

3.3 Feasibility of using other bands

It is not at all desirable to move altimeter operations to other bands. There is a very large database from altimeters operating in the band 13.25-13.75 GHz. This database has established many facets required for altimetry, such as electromagnetic bias of the sea surface around 13.5 GHz; an exact model of the interaction of the surface features and the RF pulse; atmospheric effects on the RF attenuation and delay; and spacecraft attitude effects on the return waveshape, to name a few.

Translating all of this data to another frequency band would be a considerable task, if it could be done at all, without actual flight data. Currently, the JASON altimeter has a secondary frequency (5.3 GHz) for determining ionospheric effects. The following requirements would be applicable to any new frequency chosen:

– at whatever frequency an altimeter was designed to operate, it would require a minimum of 500 MHz of bandwidth to not only meet current precision requirements but to also support potential future capabilities. Anything less would eliminate the opportunity to produce enhanced data in the future and would be unacceptable to the science community;
– the altimeter is intended to be an all-weather instrument. It is required to obtain surface data 90% to 95% of the time. Using allocated frequencies above 20 GHz, the altimeter measurement would be degraded by both clouds and rain. In the band 13.25-13.75 GHz, these effects can be compensated for except during very heavy rain events. At 35 GHz,

these effects would significantly degrade the altimeter operation and could not be adequately compensated for; mission objectives could not be met;

– spacecraft hardware must fit within cost and weight constraints. At the lower frequencies (i.e. below 5 GHz), the hardware would become considerably larger and heavier. To obtain the required signal/noise ratios for precision tracking at lower frequencies would require larger antennas. Since future missions are being directed as smaller, lower cost, and more lightweight systems, this would not be feasible. Other problems, such as inadequate allocated bandwidth, exist in all of the lower frequency bands.

3.4 Continued need for the 13.25-13.75 GHz band for altimeters

The only allocated band where altimetric mission requirements can be met is the band 13.25-13.75 GHz, where extensive databases have evolved and where simulators, models and space-qualified hardware have been developed. Currently envisioned and future designs potentially requiring up to 500 MHz can also be accommodated in this band.

4 Precipitation radars

4.1 The use of the 13.25-13.75 GHz band by precipitation radars

Although there are several frequencies allocated to spaceborne radars (e.g. 9.6 GHz, 13.5 GHz, 17.2 GHz and 35.5 GHz), the 13.25-13.75 GHz band was selected as the most suitable frequency band for precipitation radars (PR), especially single-band radars such as the tropical rain measuring mission (TRMM) PR. The major system requirements which determined this frequency selection are:

a) dynamic range and sensitivity of rainfall measurements;

b) instantaneous field-of-view (IFOV) vs. antenna size; and

c) signal-to-ground clutter ratio.

It is noted that using frequency bands above the band 13.25-13.75 GHz alone cannot adequately satisfy the requirement a), and that the requirements b) and c) are difficult to be met with the use of frequency bands below the band 13.25-13.75 GHz.

The TRMM PR, which was the only spaceborne PR appearing before the year 2000, was developed by NASDA, Japan. TRMM PR operated on a secondary basis within the band 13.75-14 GHz and was not protected from the primary services allocated to this band (as described in the background section of this Report). The Global Precipitation Measurement (GPM) mission has also been studied in relation to global hydrological studies (such as GEWEX). For the GPM mission, the 13.25-13.75 GHz band is also essential, and it would be the best choice to use the same frequency vicinity as TRMM from the cost and schedule point of view and from data continuity considerations. The GPM and FengYun Rain Measurement (FY-RM) missions are dual frequency precipitation radar using both the 13.25-13.75 GHz and 35.5-36 GHz bands for precipitation measurements. However, in this case, use of both bands is essential to meet the measurement requirements of the mission.

4.2 Bandwidth requirements

Since the range resolution requirement for the PR is not as severe as other spaceborne radars such as SAR and altimeters, the receiver bandwidth of PR is expected to be narrow (at most several MHz). However, the following facts should be considered:

– *Frequency agility:* In order to achieve high accuracy in rain echo power estimates in a short time, the frequency agility technique, which uses multiple carrier frequencies several megahertz apart from each other and transmits pulses sequentially or alternatively, will be employed. Although the bandwidth of each frequency is the same as that of non-frequency-agility radar, the total bandwidth required is significantly larger. For example, the TRMM PR used two frequencies 6 MHz apart from each other, and each frequency channel had a 3 dB bandwidth of 0.6 MHz. To achieve a sufficient attenuation of 60 dB separation, a total bandwidth of 12 MHz is required, which was used for the FSS earth station – PR interference study. In general, the number of frequency channels will be limited to three or four, so the total bandwidth required will be between 20-40 MHz depending upon the number of channels and the frequency separation.

– *Pulse-compression radar:* For future missions, pulse-compression techniques will be employed in order to achieve a higher range resolution, a high sensitivity and/or high accuracy in rain echo power estimates. The optimum chirp bandwidth of a pulse-compression radar has been reported to be 5.3 MHz. If the number of frequency channels is limited to three or four, a separation between channels of 6 MHz is required to achieve a sufficient attenuation with the individual channel chirp bandwidths of 5.3 MHz. Then the total bandwidth required is between 20-40 MHz. Required bandwidths for the pulse compression PR are still much less than the 320-500 MHz required by spaceborne altimeters.

– *RF bandwidth*: Although the final bandwidth of a radar receiver is determined by a narrow band-pass filter, it is necessary to evaluate the response of the radar receiver to out-of-band interference signals, because the bandwidth of the receiver front-end up to the IF unit at which the narrow band-pass filtering is performed is generally much wider. This can cause the saturation of the receiver front-end. The out-of-band interference signal may also appear in the radar video signal due to the finite attenuation of the band-pass filters.

In summary, the bandwidth of future spaceborne PR would be at most 40 MHz. Consideration of the receiver RF bandwidth, which is generally much wider than the final pass band, is also necessary.

4.3 Feasibility of using other bands

This section considers the frequencies suitable for future space rain measurement missions (based upon the above general discussion). It begins with the case of single-band radar followed by a brief discussion on dual-band radar. The single-band radar is considered as a baseline instrument for any follow-on missions to TRMM.

4.3.1 Measurement dynamic range

Frequencies higher than 17 GHz cannot satisfy the requirement of rain rate measurement dynamic range between about 1 mm/h and 50 mm/h throughout the precipitation layer, which is based on a statistical study of tropical oceanic rainfall. The 35.5-36 GHz band is a candidate for the measurement of precipitation at higher latitudes where light rainfall and snow would be dominant, i.e. for measurement of minimum precipitation rates starting around 0.1 mm/h. For tropical rainfall, however, this frequency is too high to obtain a sufficient dynamic range throughout the precipitation layer due to the attenuation within this layer around 35.75 GHz.

4.3.2 Instantaneous field of view (IFOV)

In order to achieve an IFOV of the order of 5 km from a typical LEO altitude of 500 km, the beamwidth should be about 0.01 rad (~0.6°). That is, the antenna size should be about 100 λ or greater. In the case of the TRMM PR, the antenna size was about 2 m × 2 m^2 (~92 λ). This size had been determined from the scientific requirement for the IFOV, the limitation in antenna fabrication accuracy and the size of launching rocket fairing.

To achieve the same IFOV with a lower frequency, a larger antenna size would be required which makes the antenna fabrication and the interfaces with the spacecraft and the rocket more difficult. A conclusion in the TRMM PR feasibility study was that the use of 10 GHz or lower frequencies was technically difficult. Although the situation may change to some extent depending upon the spacecraft and rocket capabilities, the use of frequencies lower than 10 GHz, which requires an antenna of about 5 m or larger, is not currently feasible for a PR on board a spacecraft.

4.3.3 Signal-to-clutter ratio (*S*/*C*)

The requirement of the *S*/*C* depends upon the minimum rainfall rate that should be measured. There are two types of surface clutters to be considered; one is the clutter caused by antenna side lobes and the other is that caused by range side lobes appearing in the receiver filter output pulse. The latter can be particularly serious in the case of pulse-compression radars. The maximum surface clutter can reach about 60 dB higher that the rain echo corresponding to the 1 mm/h rain, which requires very low antenna side-lobe levels. TRMM PR antenna aperture distribution adopted a Taylor weighting with $SL = -35$ dB to achieve low side-lobe level characteristics. A performance analysis has demonstrated that the PR can achieve the minimum *S*/*C* of about 4 dB for 0.7 mm/h rain rate. If the frequency is lowered to 9.6 GHz, however, the strength of rain echo relative to surface clutter will decrease by about 6 dB, which will cause loss of rain detection capability at light rain rates.

In summary, the use of frequencies lower than 10 GHz for spaceborne rain radar is difficult due to increased *S*/*C* which prevents detection of low rain rates.

4.3.4 Frequencies for dual-band radars

In the case of dual-band radars in order to achieve wider dynamic range and higher accuracy in precipitation retrieval, the selection of radar frequencies becomes more complicated. If the major objective is rain measurement, combinations of 9.6 and 24 GHz, 13.5 and 35.5 GHz, and 13.5 and 24 GHz would be desirable. If the objective is to measure both rain and cloud, the frequency selection would be an independent decision process of a single-band rain radar and a single-band cloud radar.

In either case, the frequency band 13.25-13.75 GHz will remain essential for future dual- (or multiple) band radars, as it provides global coverage (both tropical and higher latitude rain), sufficient dynamic range of measurement, and is technically feasible with respect to the requirements of spatial resolution and *S*/*C*.

4.4 Continued need for operation in the 13.25-13.75 GHz band

For the single-band radars used for tropical rainfall measurement, the frequency band 13.25-13.75 GHz remains essential because:

– from the point of view of measurement dynamic range, frequencies at 17.2 GHz and higher are too greatly attenuated to retrieve accurate data on the precipitation rates throughout the precipitation layer for higher (i.e. tropical and sub-tropical) precipitation rates;

– a shift from the frequency band 13.25-13.75 GHz to near 9.6 GHz would require significant design changes in the radar equipment to achieve the same resolution and sensitivity, although advances in antenna technology may make the use of lower frequencies feasible for some future missions.

The importance of the 13.25-13.75 GHz frequency band also holds for the future dual-band radars. This band has been used for several spaceborne scatterometers and altimeters. The heritage and databases in radar hardware and scattering cross-section data are very useful for continuing development of spaceborne PR. Since the TRMM PR used the band near 13.5 GHz, many algorithms have been developed for this frequency, which can only work around 13.5 GHz.

Considering the past heritage, databases, rain rate measurement requirements and on-going efforts, it is essential to maintain the 13.25-13.75 GHz frequency band for current and future spaceborne PR.

5 Summary and conclusions

This Report addresses the use of the 13.25-13.75 GHz band and bandwidth requirements for spaceborne active sensors, as well as the possibility/feasibility of using bands other than the 13.25-13.75 GHz band to satisfy mission requirements. This Report also addresses the long-term need for access to the 13.25-13.75 GHz band from the viewpoint of three major active sensor applications currently operating in this band, i.e. scatterometers, altimeters and precipitation radars. Based on these studies, the following conclusions are drawn:

- *For scatterometers:*
  - in the late 1990s scatterometers operated at a centre frequency of 13.995 GHz; current scatterometers have been designed to operate at 13.402 GHz;
  - current generations of scatterometers require bandwidths up to 5 MHz in the 13.25-13.75 GHz band;
  - future scatterometers are expected to use spread spectrum modulation in order to obtain more precise definition of the surface cell where wind measurements are being taken. The bandwidth requirement for these future instruments would be much higher than 5 MHz and up to 100 MHz to improve measurements through the use of alternative modulation techniques;
  - the use of bands allocated to the EESS (active) other than the 13.25-13.75 GHz band is not an acceptable alternative. This is due to the optimality of the frequency band 13.25-13.75 GHz for the physical phenomenon being observed as well as the significant investments that have been made to develop databases, data reduction algorithms, ground stations and space-qualified equipment.
- *For altimeters:*
  - the first generation of altimeters used bandwidths of approximately 320 MHz centred at 13.575 GHz, 13.60 GHz, 13.65 GHz and 13.80 GHz;
  - access to the 13.75-14 GHz band was required through 1997 for TOPEX-POSEIDON and through 2000 for ERS. Since altimeters are no longer protected by the primary services allocated to this band, the altimeters on both JASON and ENVISAT were moved down in frequency so that they do not require access to the 13.75-14 GHz band;
  - while 350 MHz is the current maximum bandwidth used, future altimeters will require bandwidths up to 500 MHz and operate over the entire 13.25-13.75 GHz band;
  - in addition, a bandwidth of 500 MHz will be required to accommodate both an altimeter and a scatterometer on the same spacecraft;
  - altimeters were primarily ocean remote sensing instruments but radar altimeter missions (such as SRAL on SENTINEL-3 mission) are now to acquire topography data

and meet their requirements over all types of surfaces (sea, coastal areas, sea ice, ice sheets, ice margins and in-land waters);

– the use of other EESS (active) bands than the 13.25-13.75 GHz band is not an acceptable alternative because of the optimality of the frequency band for the physical phenomenon being observed and on the basis of substantial economic investments that have been made to develop databases, data reduction algorithms, ground stations and space-qualified equipment.

• *For precipitation radars:*

– the previous generation of precipitation radars launched in 1997 was flown on board TRMM and operated at 13.796 GHz and 13.802 GHz (two-channel frequency agility) each with a receiver bandwidth of 1.72 MHz;

– the current generation of precipitation radars operate in the 13.25-13.75 GHz frequency band;

– a bandwidth of up to 40 MHz will be required to accommodate next generation PR;

– the use of bands allocated to the EESS (active) other than the 13.25-13.75 GHz band is not an acceptable alternative on the basis of dynamic range of measurement (for tropical rainfall), IFOV, and spacecraft design requirements;

– considering past heritage, databases, rain rate measurement requirements and on-going efforts, it is essential to maintain the frequency band 13.25-13.75 GHz for current and future spaceborne PR.

Overall, it is concluded that it is essential to ensure the continued and long-term availability of the band 13.25-13.75 GHz for operation of spaceborne active sensors in the EESS (active).